New Technologies for Particle Accelerators at the Energy Frontiers

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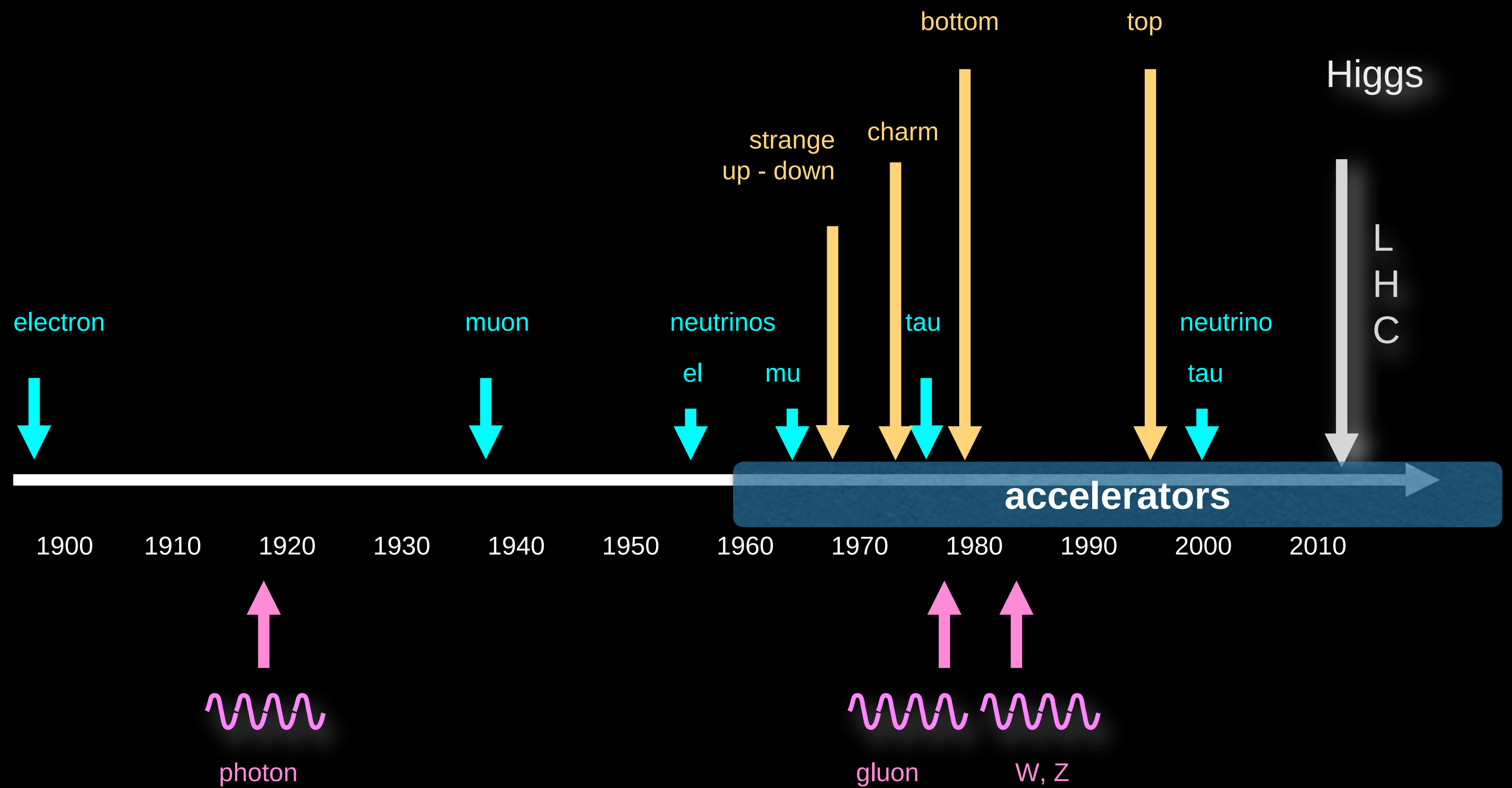
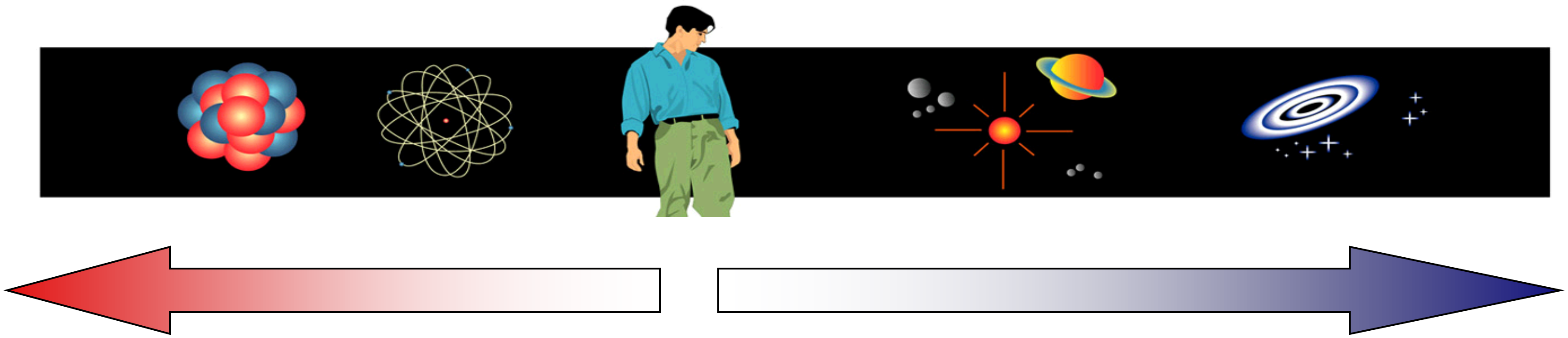
SAPIENZA
UNIVERSITÀ DI ROMA

60 years of experiments at accelerators have discovered the set of fundamental particles



Accelerators gain us one frontier of the physics spectrum



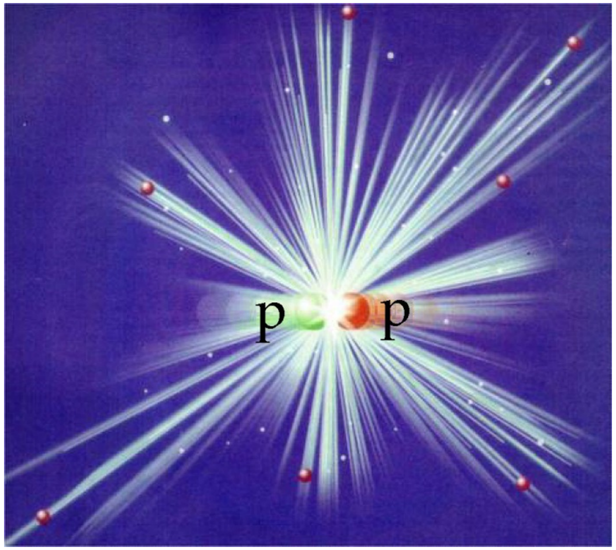
Accelerators | Microscopes | Binoculars | Optical, radio télescopes

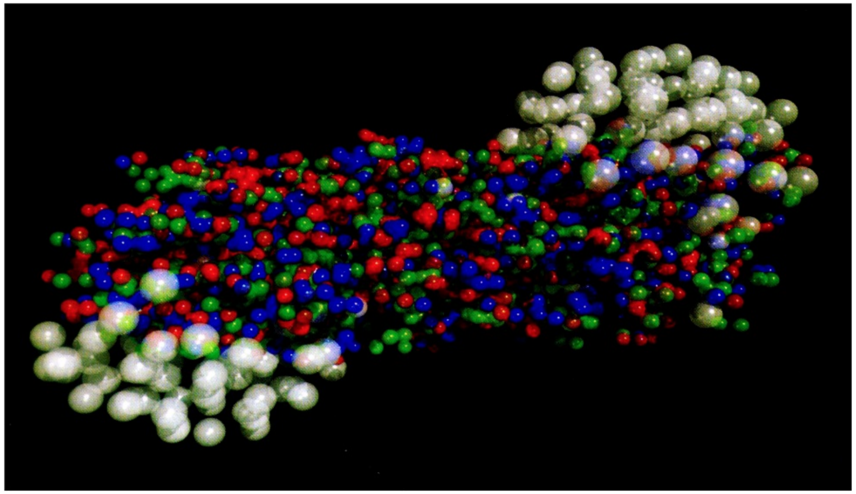
Particle physics looks at matter in its smallest dimensions and accelerators are very fine microscope or, better, *atto-scope!*

$\lambda = h/p$; @LHC: $T = 1$ TeV $\Rightarrow \lambda \cong 10^{-18}$ m = 1 am (actually 30 zm)

…back to Big Bang

- Trip back toward the Big Bang: $t_{\mu s} \cong 1/E^2_{Gev}$
- $T \cong 1$ ps for single particle creation
- $T \cong 1$ μs for collective phenomena QGS (Quark-Gluon Soup)





But we are left with the task of explaining how the rich complexity that developed in the ensuing 13.7 billion years came about…

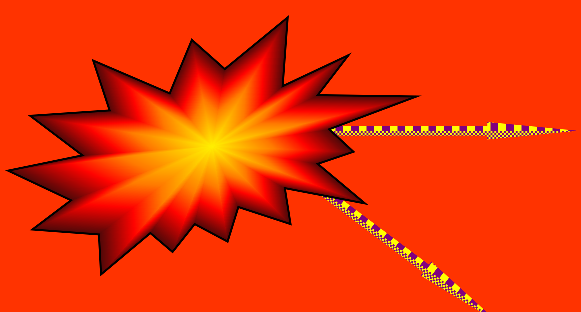
Which is a much more complex task!

Accelerators: the two frontiers

2 routes to new knowledge about the fundamental structure of the matter

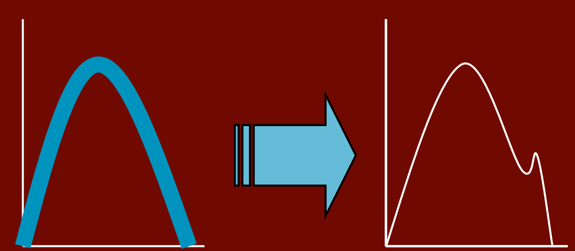
High Energy Frontier

New phenomena (new particles) created when the "usable" energy > mc^2 [×2]

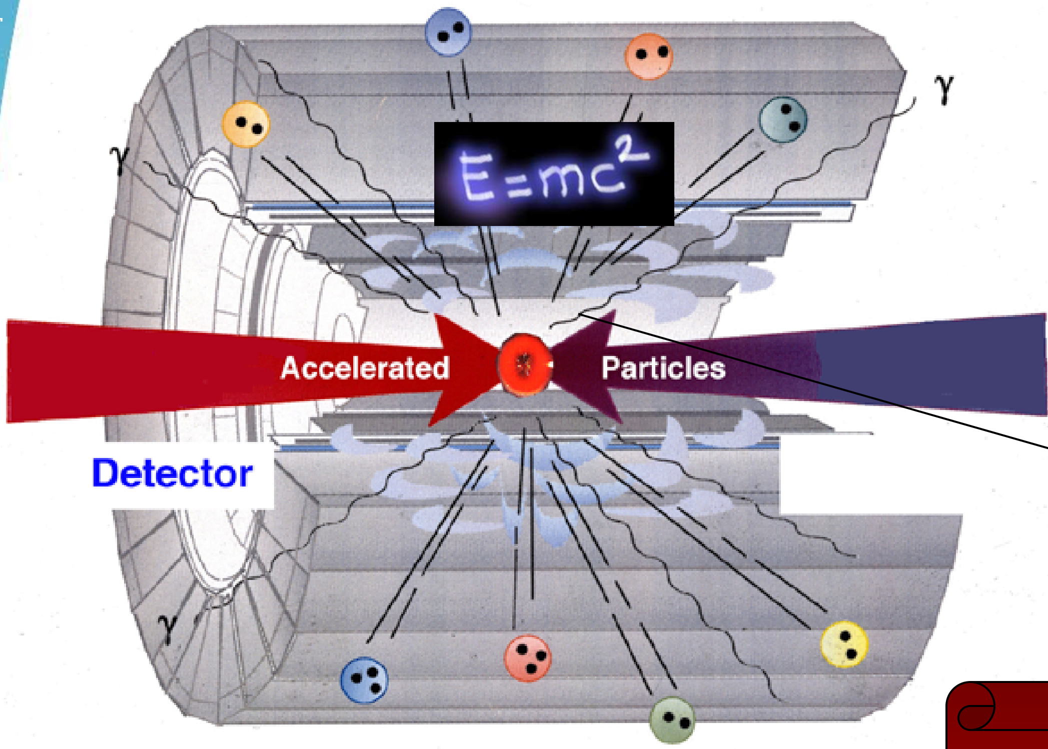


High Precision Frontier

Known phenomena studied with high precision *may* show inconsistencies with theory



The method of HEP colliders



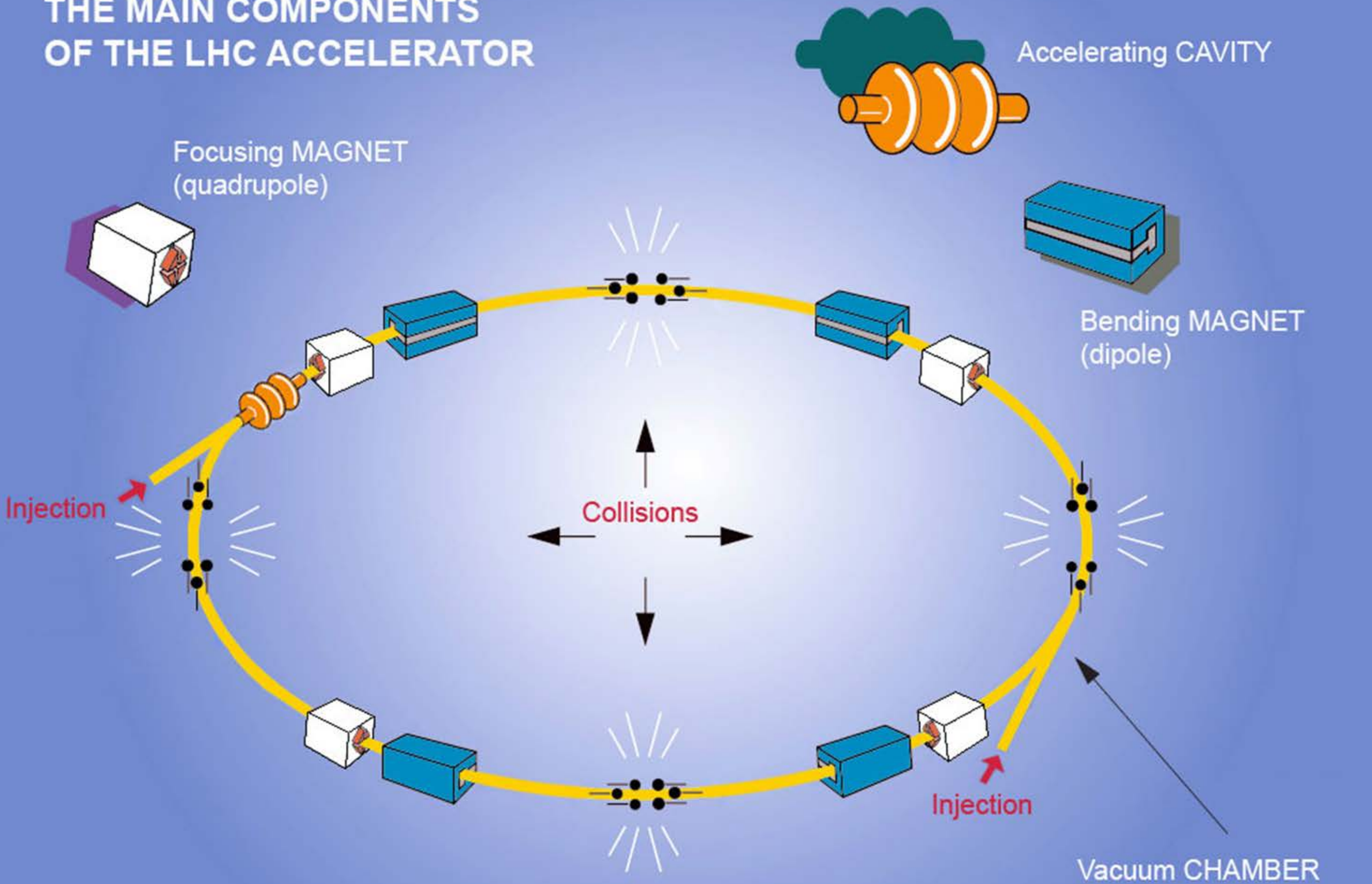
1) Concentrate energy on particles (**accelerator**)

2) **Collide** particles (recreate conditions after Big Bang)

3) Identify created particles in **Detector** (search for new clues)

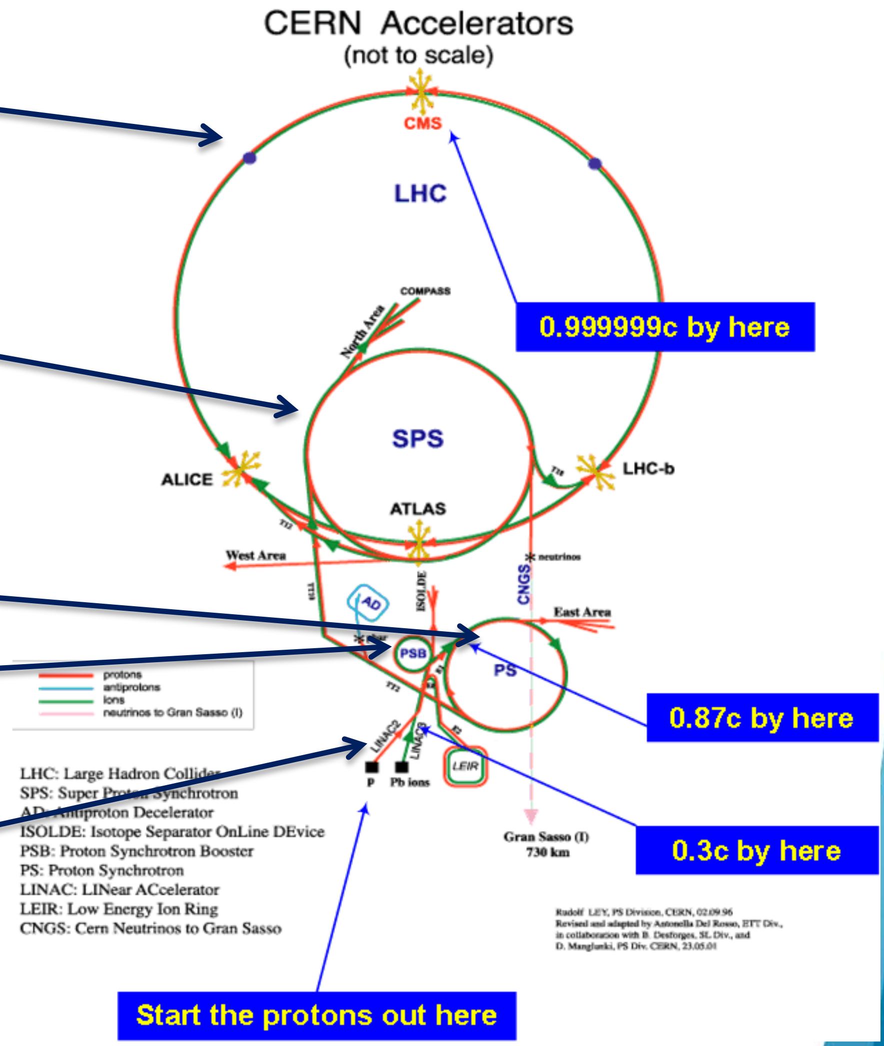
And both of them need high technology like superconductivity

THE MAIN COMPONENTS OF THE LHC ACCELERATOR



CERN proton accelerator chain

- LHC : 2x(0.45 – 7) TeV
- SPS : 26 – 450 GeV
- PS : 1.4 - 26 GeV
- PSB : 0.05 -1.4 GeV
- Linac: 0-50 MeV

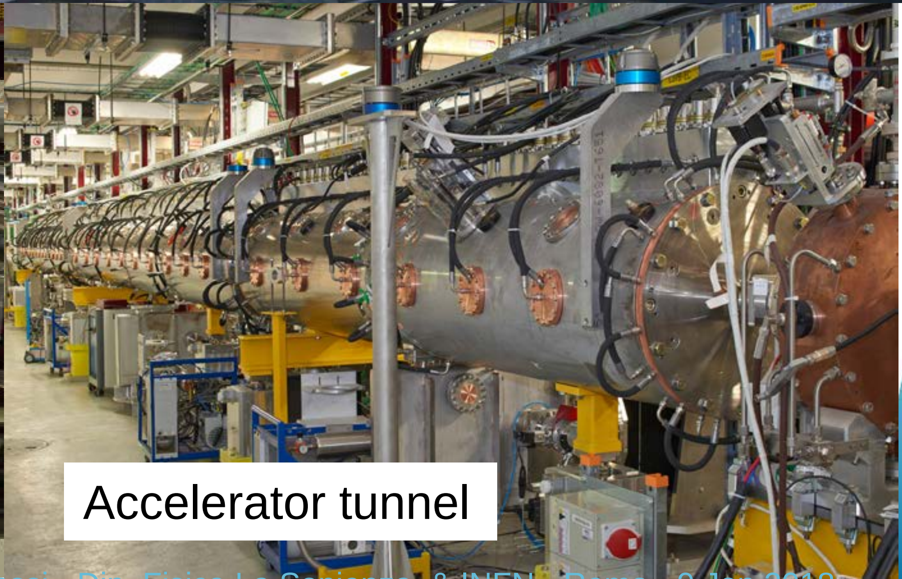


SOURCE and LINAC2

Duoplasmatron source

Linac2 : in evidence the accelerating RF structure

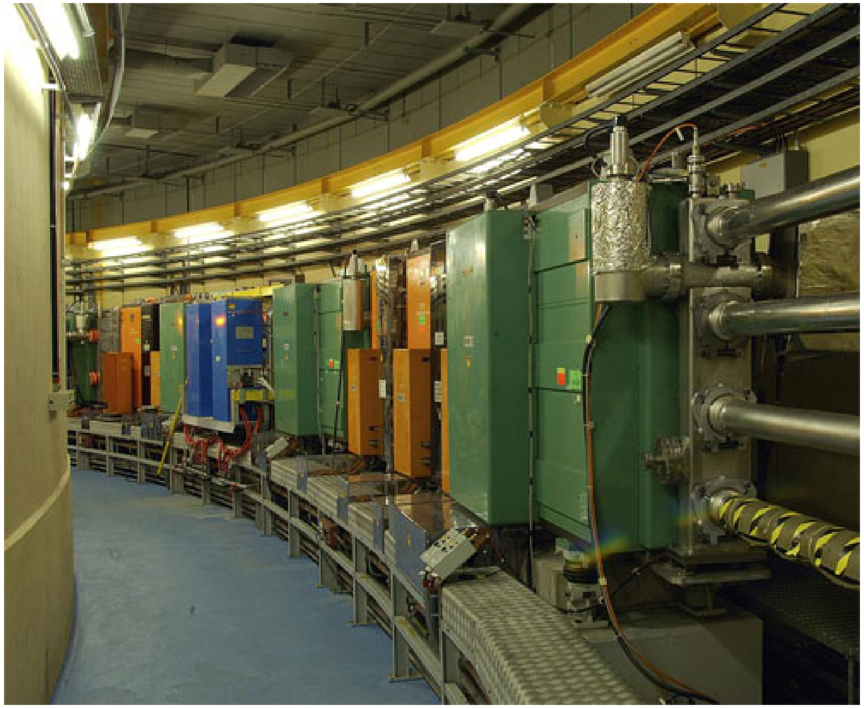
Upgrade : LINAC4 (2016, in use from 2020) H^- and 160 MeV



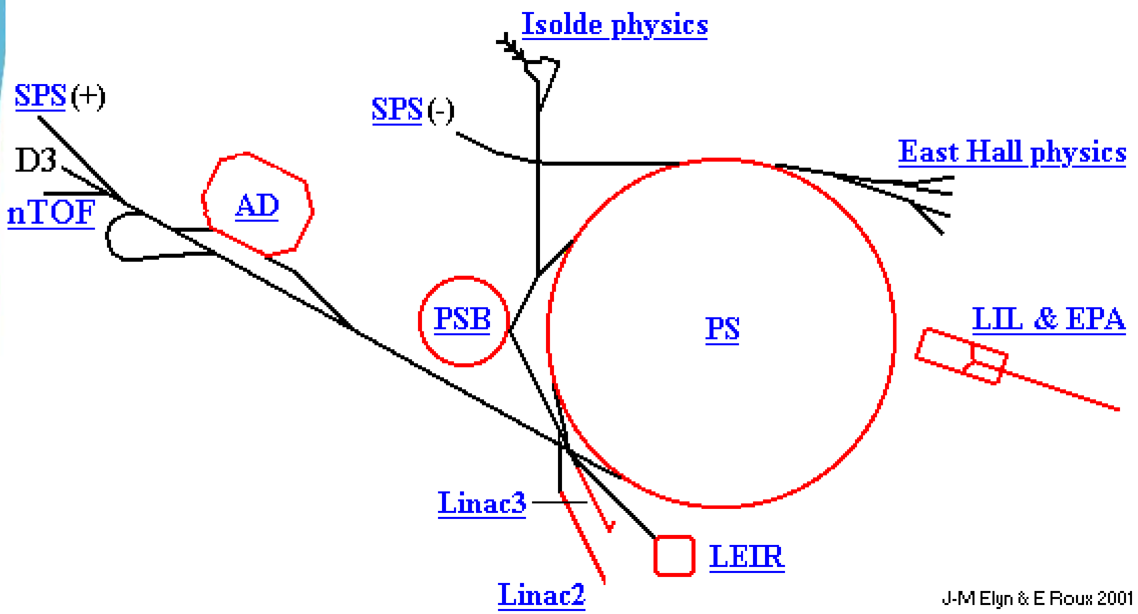
PSB (Booster): 1.4 GeV

Magnetic structure of PSB
Length : 150 m

Actually are four rings. Each beam is injected in the PS



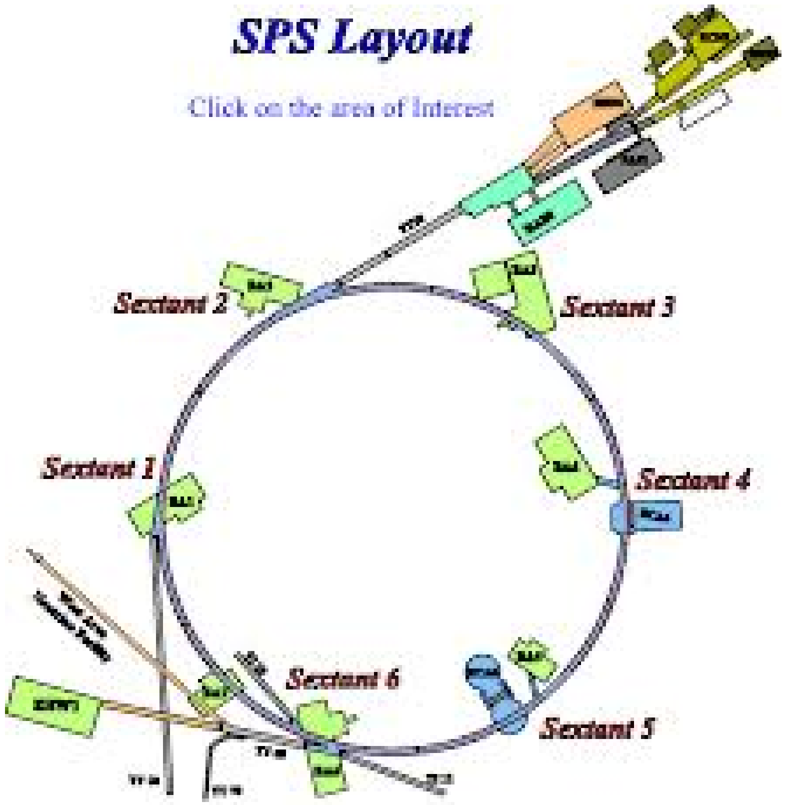
The PS complex: injector for LHC and much more…



SPS: 450 GeV proton beam
(in the 1980’s worked as p-pbar)

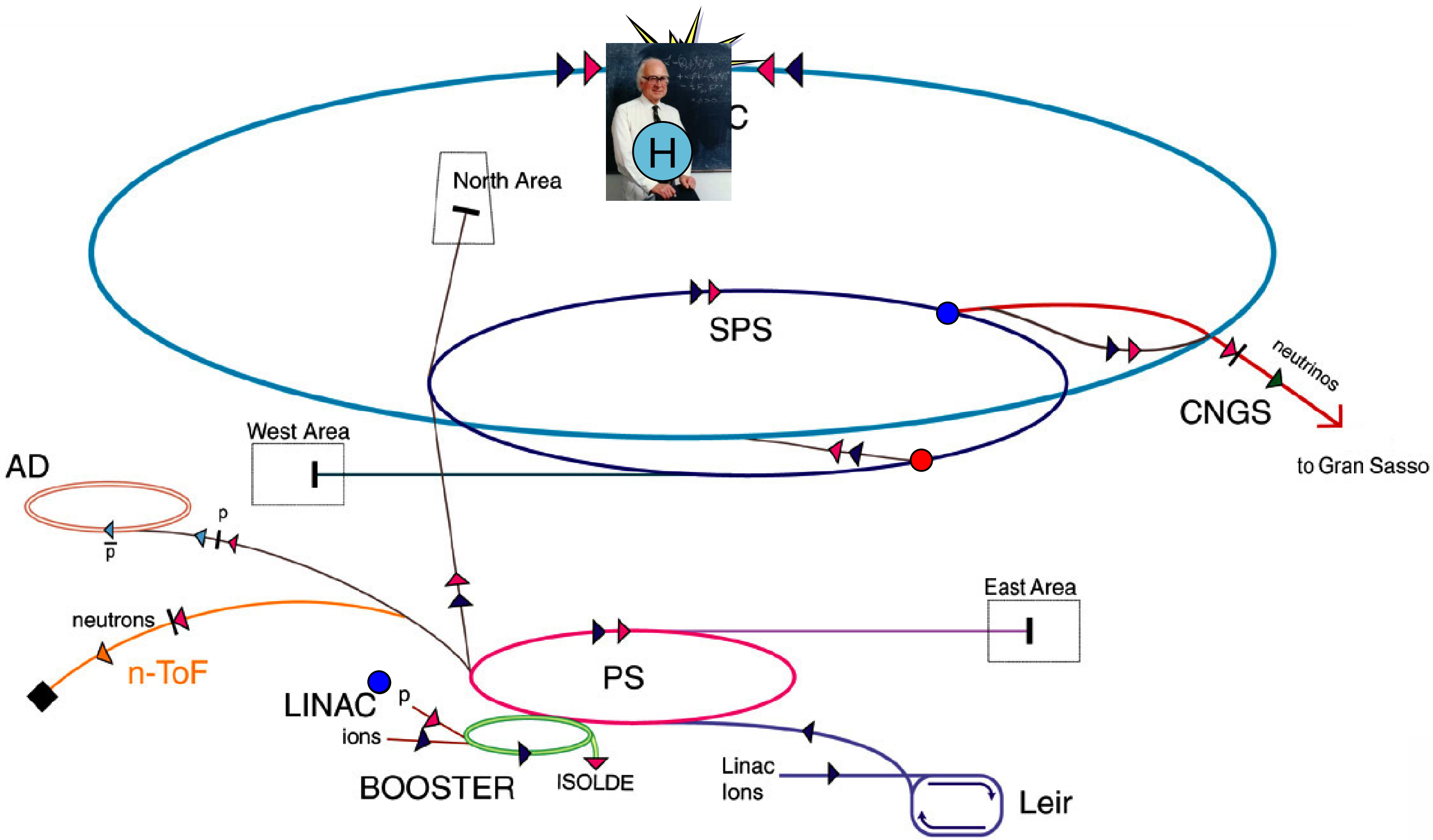
SPS tunnel (almost 7 km)

SPS complex with experimental area



CERN's particle accelerator chain: 40 km of tunnels (rings and transfer lines)

From LINAC to LHC…



p (proton)
ion
neutron

p̄ (antiproton)
proton/antiproton conversion
neutrino

AD Antiproton Decelerator
PS Proton Synchrotron
SPS Super Proton Synchrotron

LHC Large Hadron Collider
n-ToF Neutron Time of Flight
CNGS Cern Neutrinos Gran Sasso

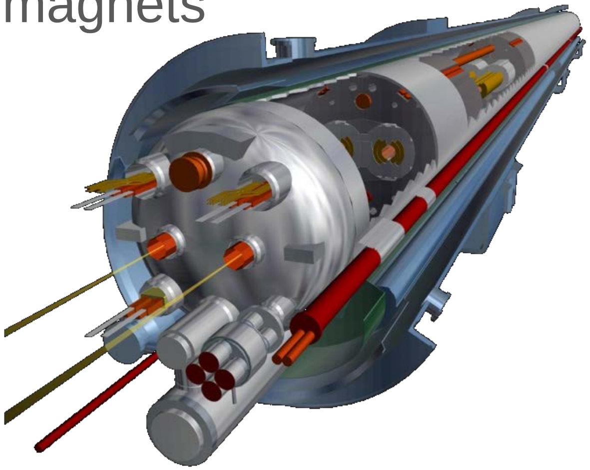
Superconducting accelerators

- <u>Circular Accelerators</u>

  E_{beam} = 0.3 ***B*** r [GeV] [T] [m]

  → superconducting bending and focussing magnets

  - high-energy hadron synchrotrons

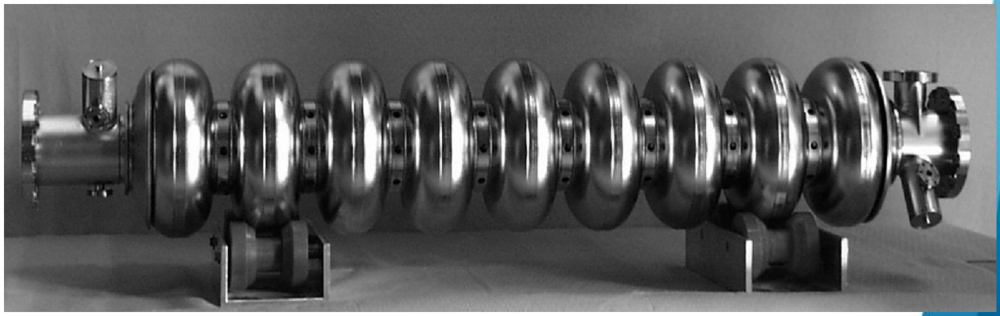


- <u>Linear Accelerators</u>

  E_{beam} = ***E*** L [MeV] [MV/m] [m]

  → superconducting acceleration cavities

  - high-energy e^+-e^- linacs



Superconductivity: an enabling technology

Cryo-pumping for beam vacuum is a big plus

- Superconducting LHC
- Tunnel : 27 km
- Field : 8.3 T
- Cryoplant power at the plug: 40 MW: **always on**
- ~ 70
- 150 acce
- 180 complex

- Normalconducting LHC
- Tunnel 120 km
- Field : 1.8 T
- Dissipated power at collisi MW
- Avera .4 coeffi MW only f or

LHC; the largest instrument

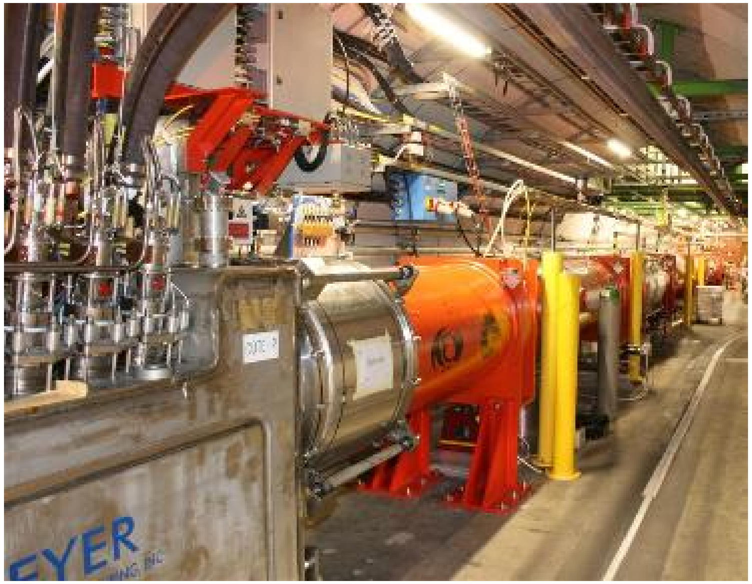
- 27 km, p-p at 7+7 TeV
  3.5+3.5 2010, 6.5+6.5 since 2014
- 1232 x 15 m Twin Dipoles
- Operational field 8.3 T @11.85 kA (9 T design)
- HEII cooling, 1.9 K with 3 km circuits (130 tonnes He inventory).

- Field homogeneity **of 10^{-4}**, bending strength uniformity better then 10^{-3}. Field quality control (geometric and SC effects) at 10^{-5}. Also during ramp up (dynamic effects)

LHC , cont.

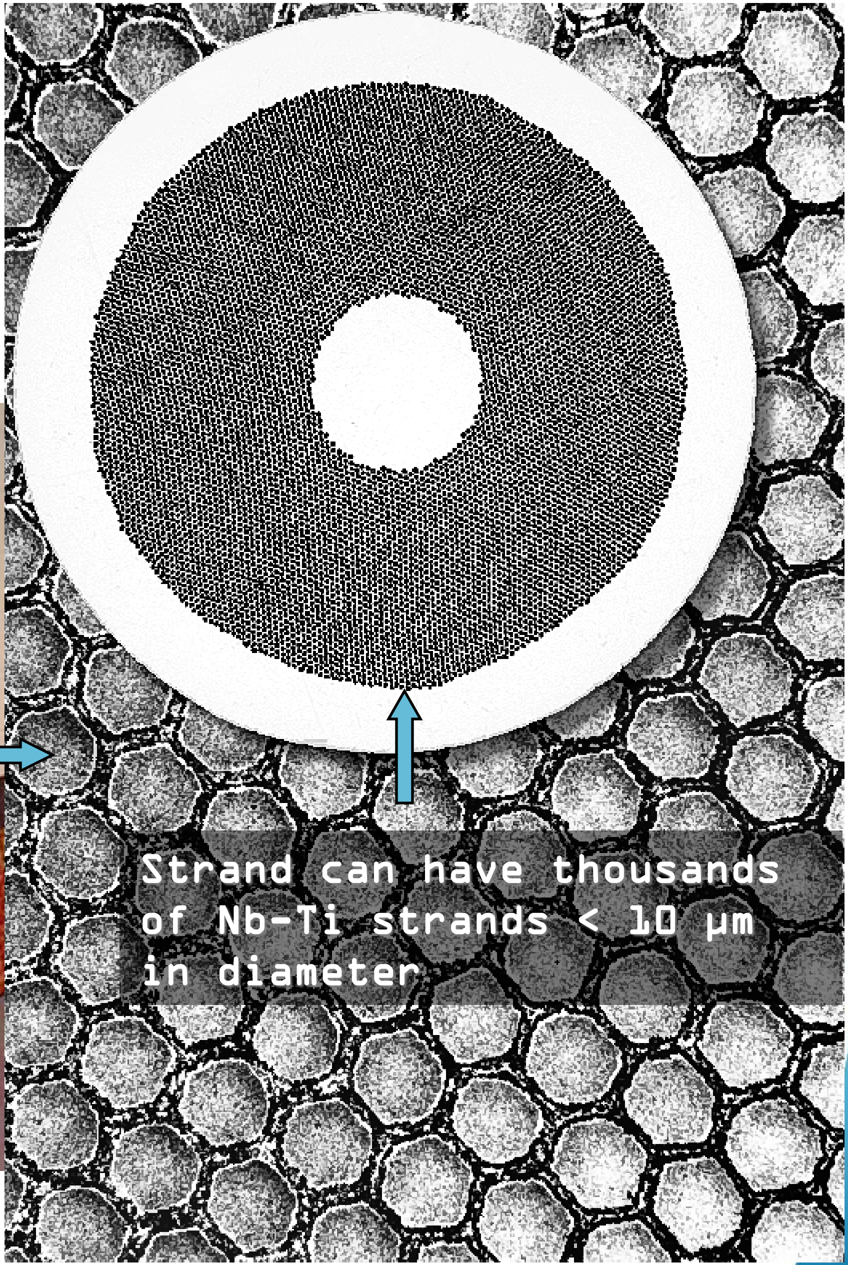
- 392 Main Quads Two-In-One rated for a peak field of 7 T.
- About 100 other Two-in-One MQs
- 32 MQX (low-β) single bore for luminosity (design L=1·10^{34} cm^{-2}s^{-1}), 70 mm apertures, about 8 T peak field, high quality
- A «zoo» of 7600 «small» Sc magnets (correctors and higher order magnets
- Total: 9 MJ stored energy (at nominal)

- Large detector magnets
  ATLAS toroid – 25 m long 1.2 GJ
  CMS solenois – 12 m long 2.5 GJ

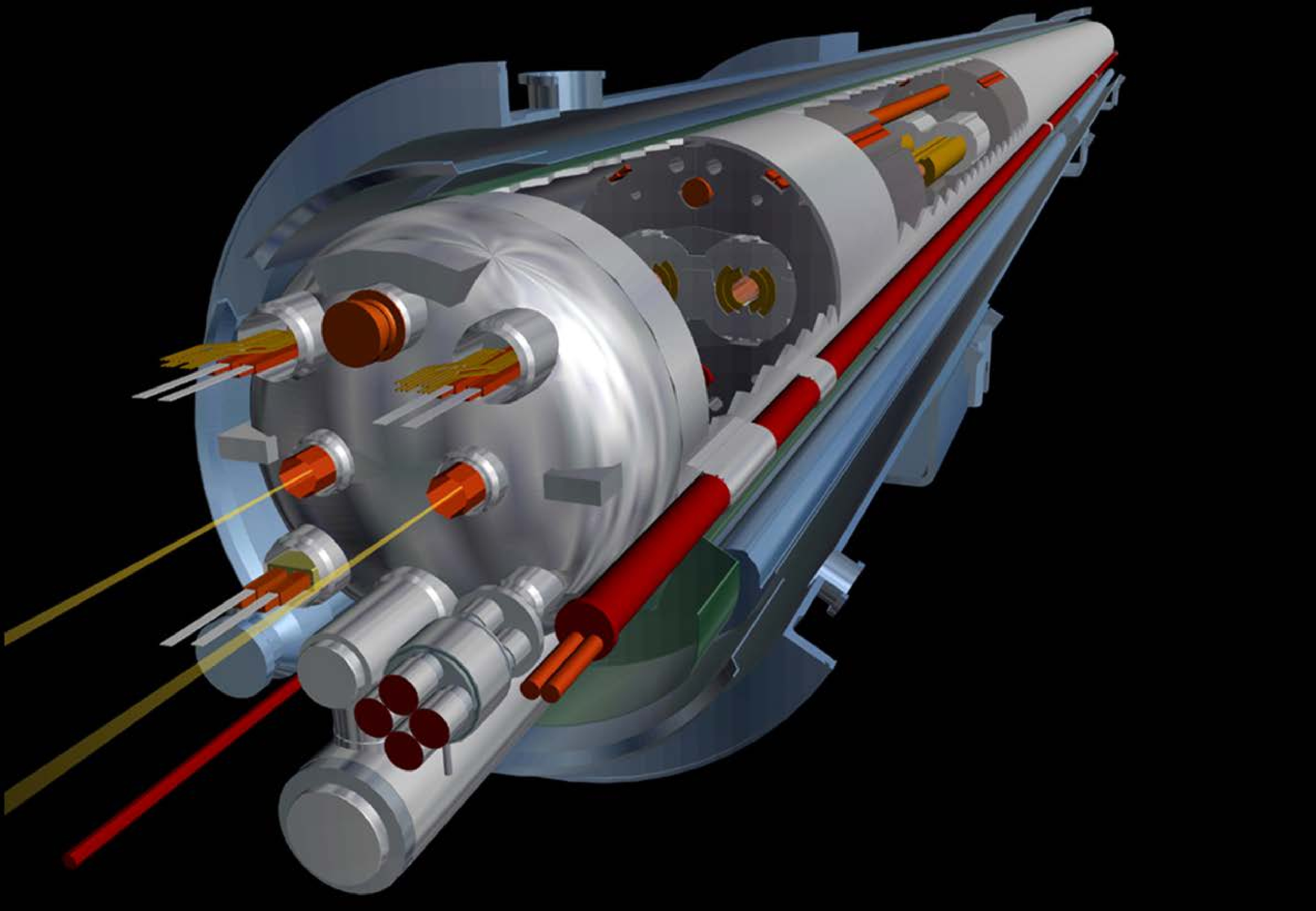


How Nb-Ti superconductor are fabricatred

30 cm diameterNb-Ti billets for LHC, courtesy Wah Chang



Strand can have thousands of Nb-Ti strands < 10 μm in diameter



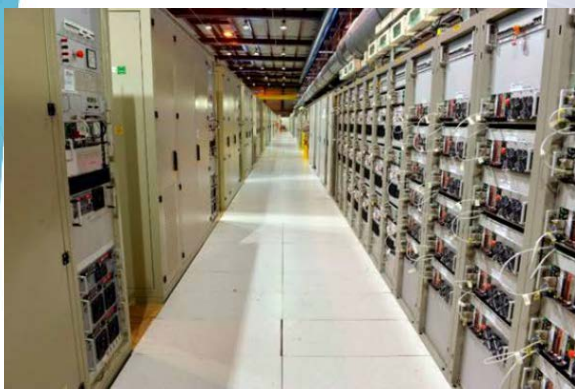
SCRF, Cryo…

400 MHz Standing wave RF

- 4 single cell cavities in cryomodule, 2 crym per beam. Total 16 cavities.
- Sputtered niobium design (as LEP)
- Gradient 5.5 MV/m nominal (8 MV/m available)
- Nominal 2MV, up to 3 MV at 8 MV/m

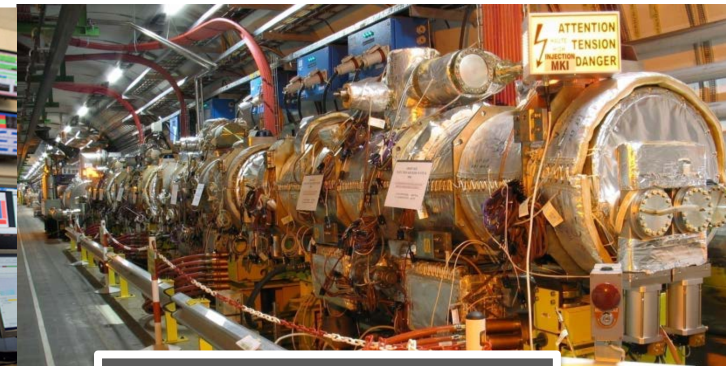
Cryo : 8 x 18 kW@4.5K

LHC: 24 km of 10,000 SC magnets … but much more than magnets



Large quantities of ultra-precise power converters

Beam Instrumentation

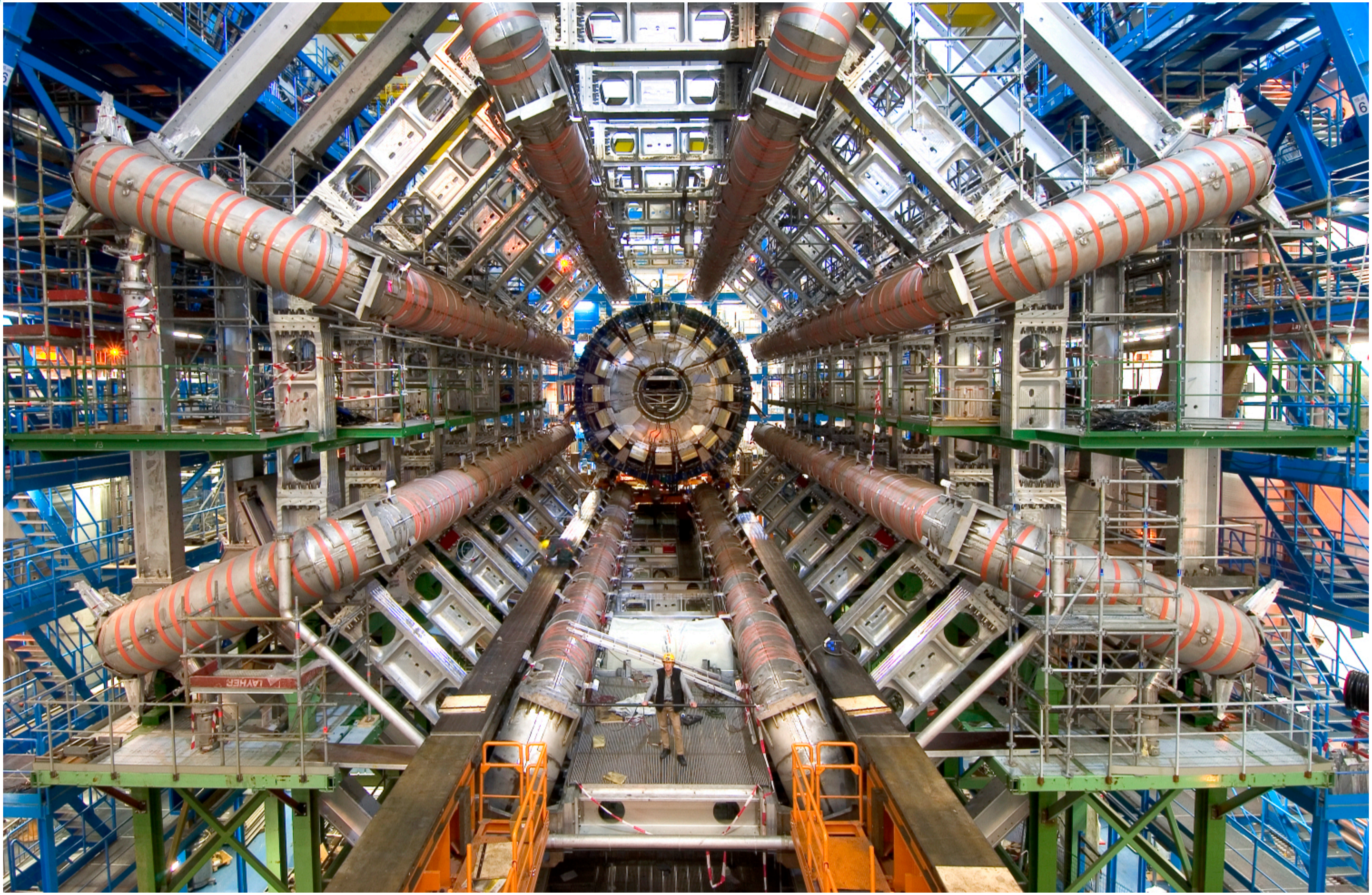


Kickers for injection

Collimators to clean > 99.9% of the losses

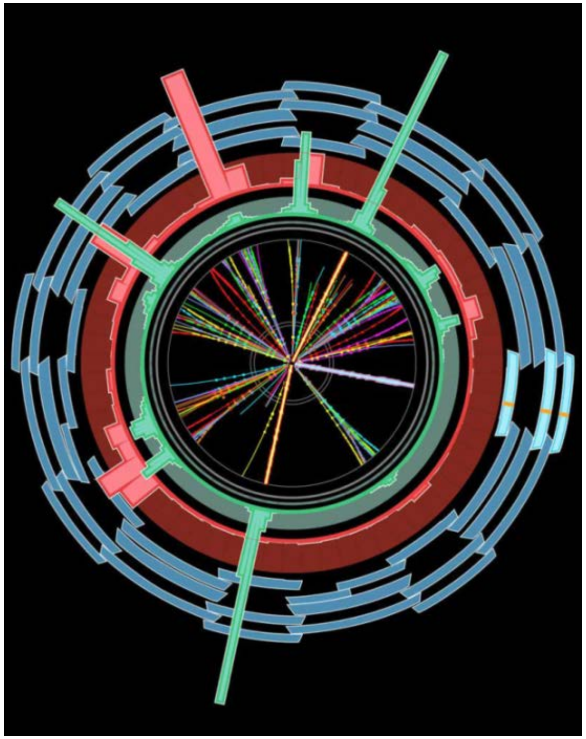
CERN Control Center

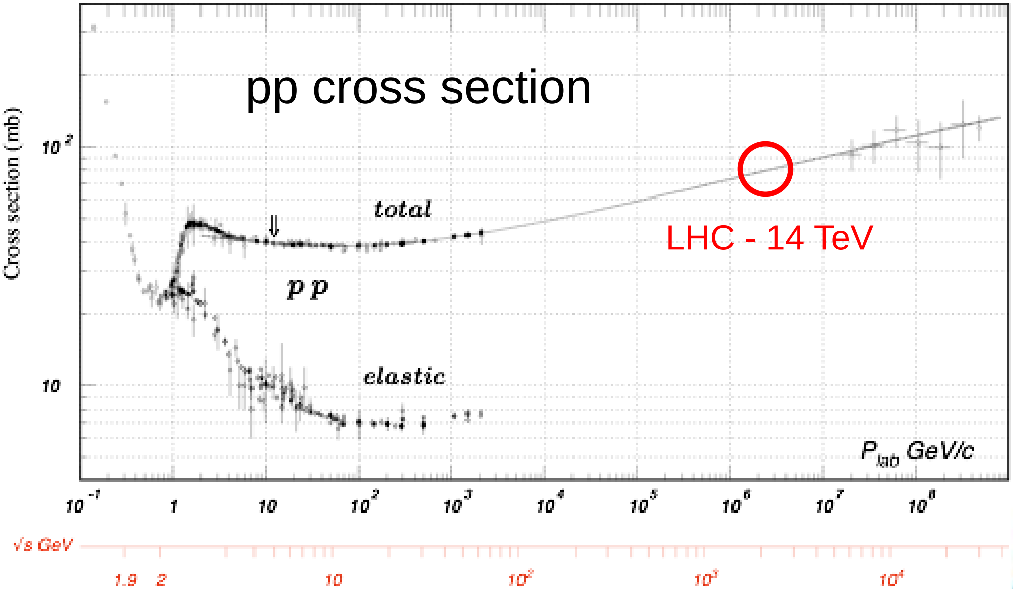
The largest eye: ATLAS SC TOROID



After energy, luminosity is the most important parameter of a collider

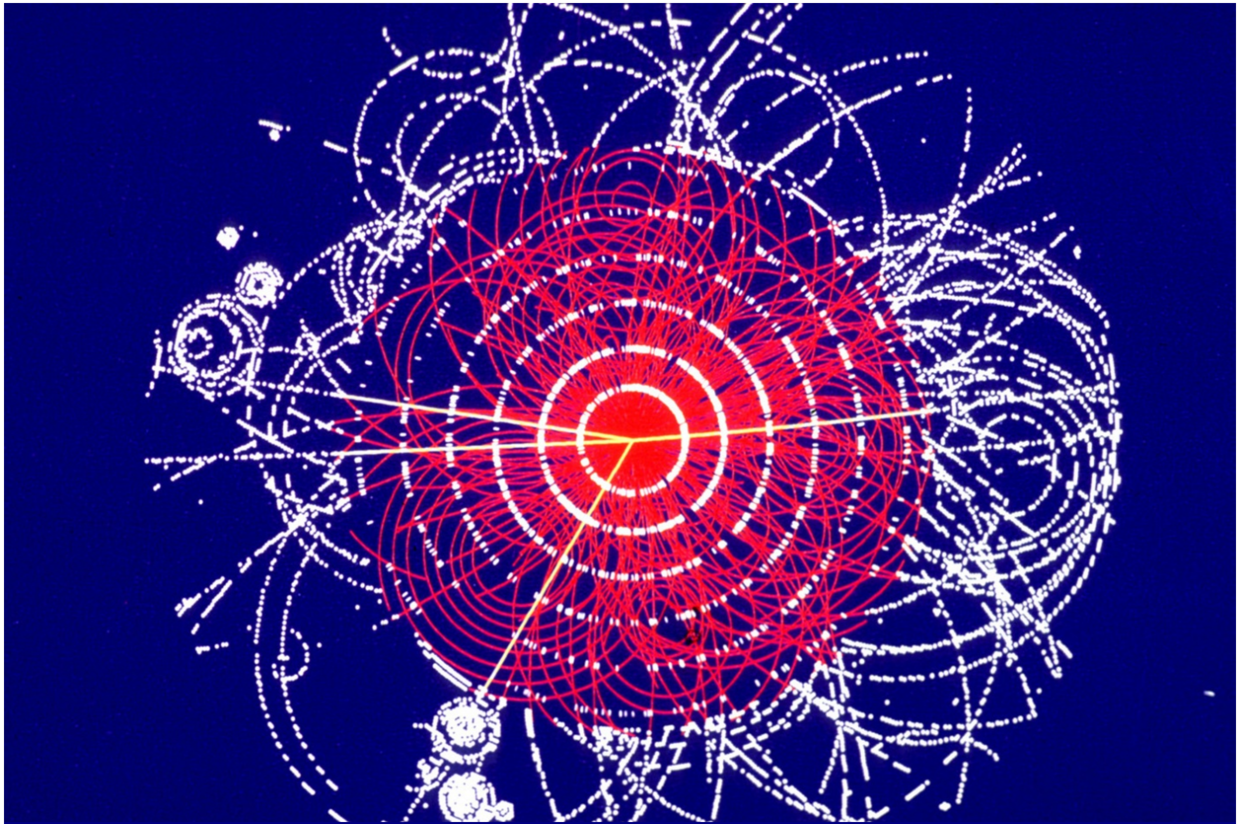
$$\frac{dN_{event}}{dt} = L\sigma_{event}$$





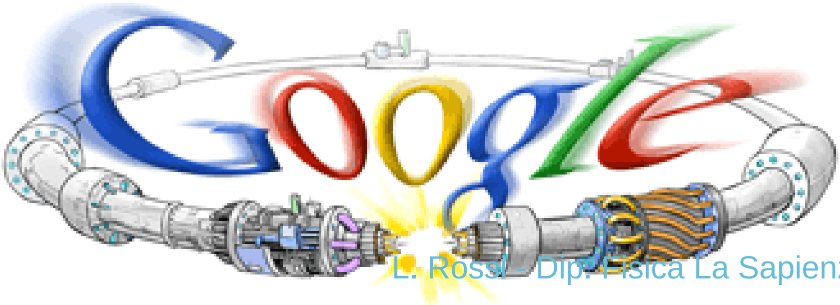
Higgs signature at LHC (computer simulation, ca. 2006)

Proton beams will cross each other 100 millions time per second !



WE EXPECT ONLY 1 HIGGS IN 1,000,000,000,000 EVENTS

10 settember 2008:The success!
10 YEARS AGO!

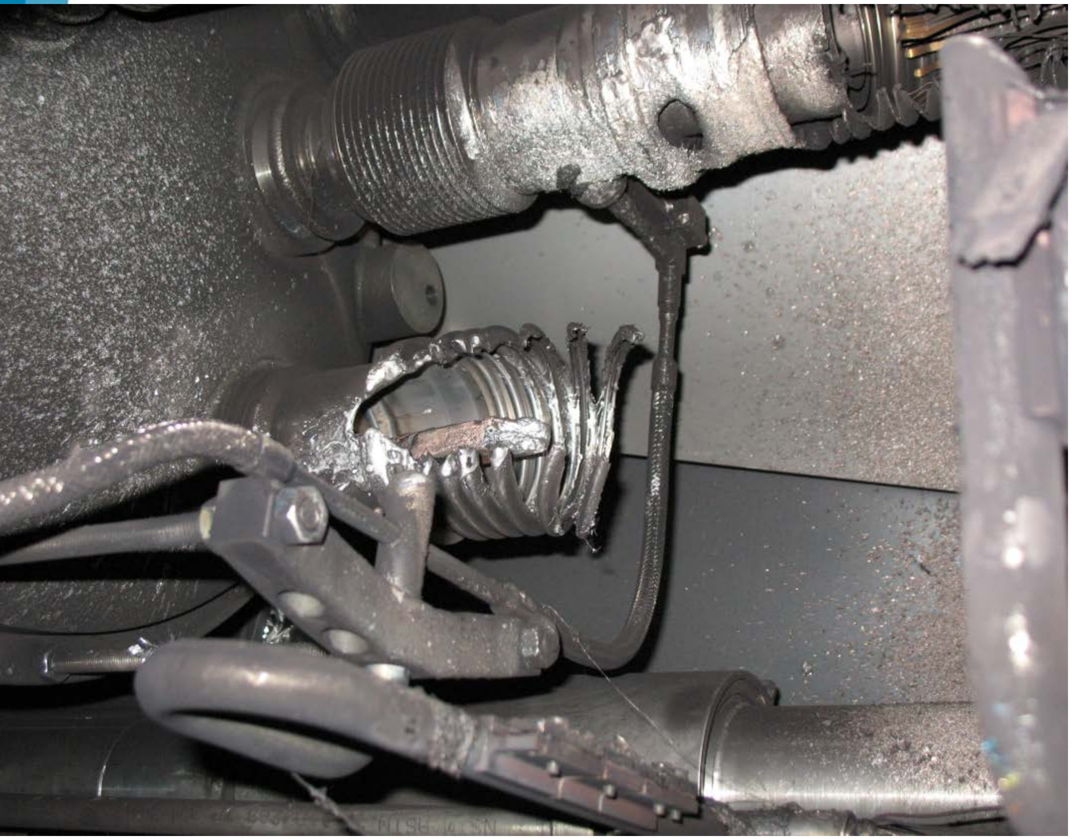


19 settember 2008:
The big trouble

Electrical connection in detail

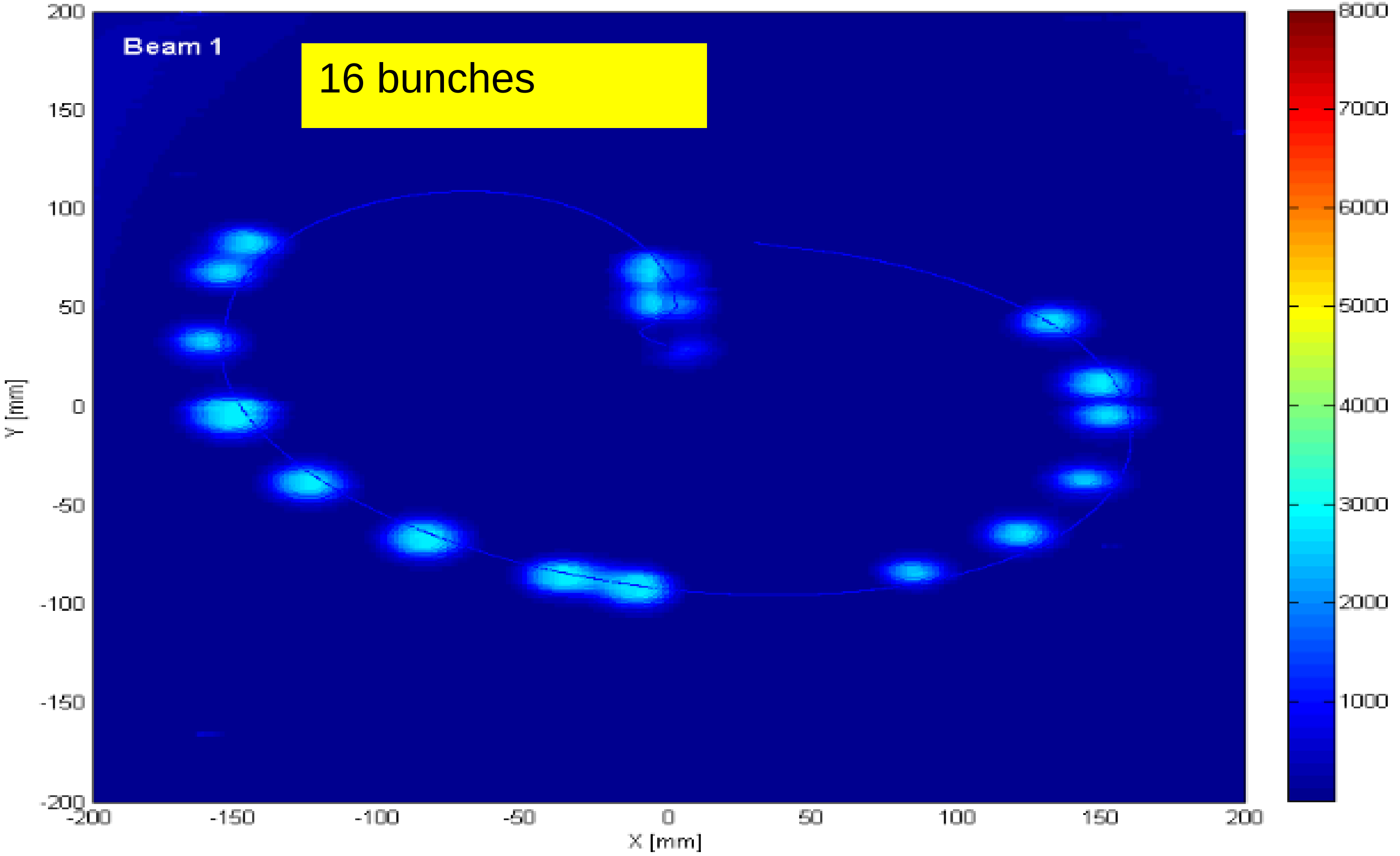
Articolo su November 2009 http://www.ilsussidiario.net/

Extended damages

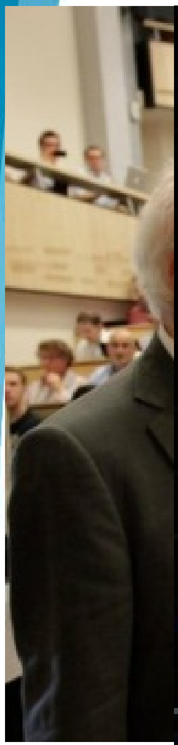


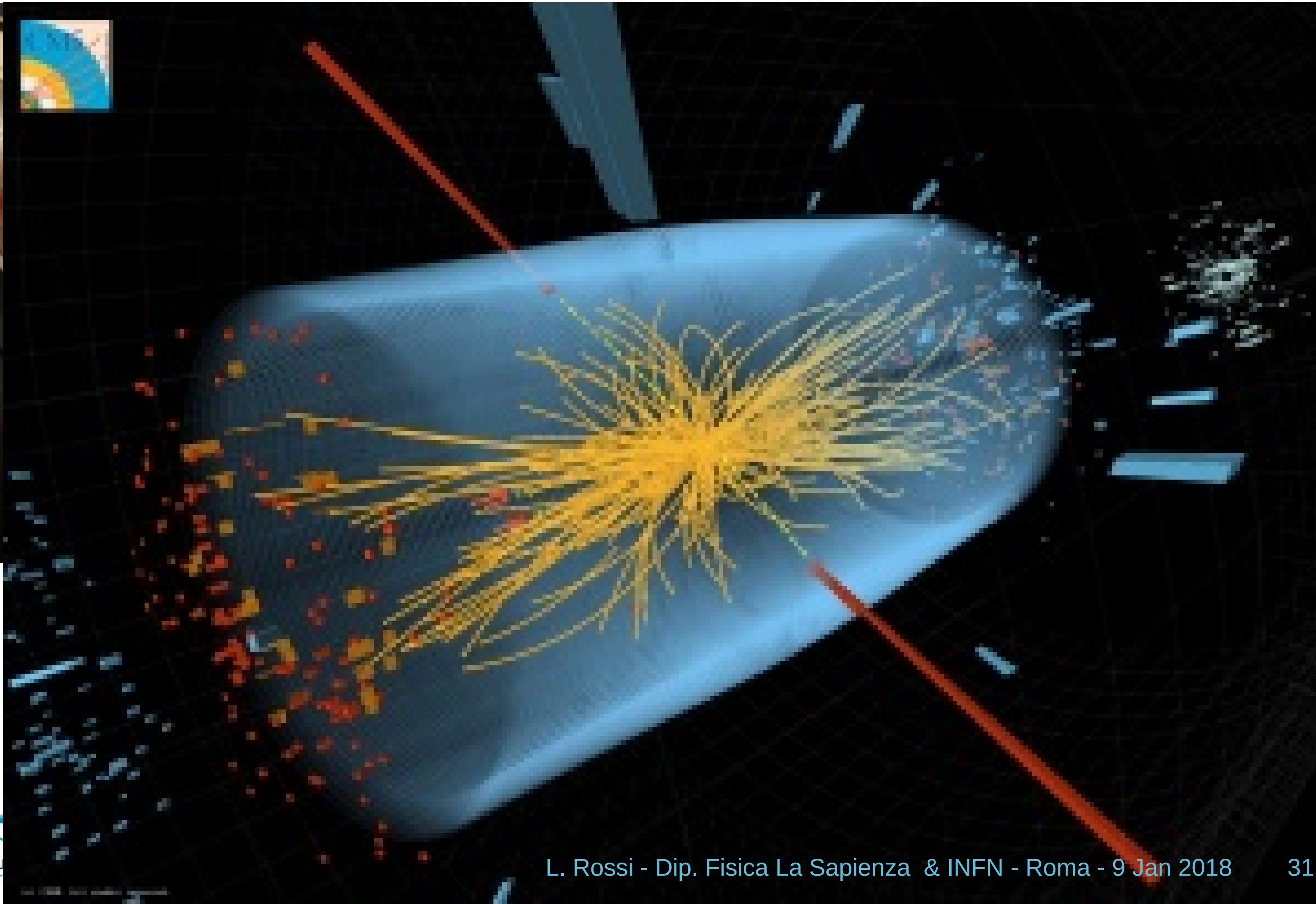
- Design not robust against not ideal procedures.
- Defects of procedure not identified by QA
- Lack of adequate diagnostics (eyes)
- No protection against collateral damage (Titanic syndrome?)

13 dicember 2009 : record 2 × 1.18 TeV



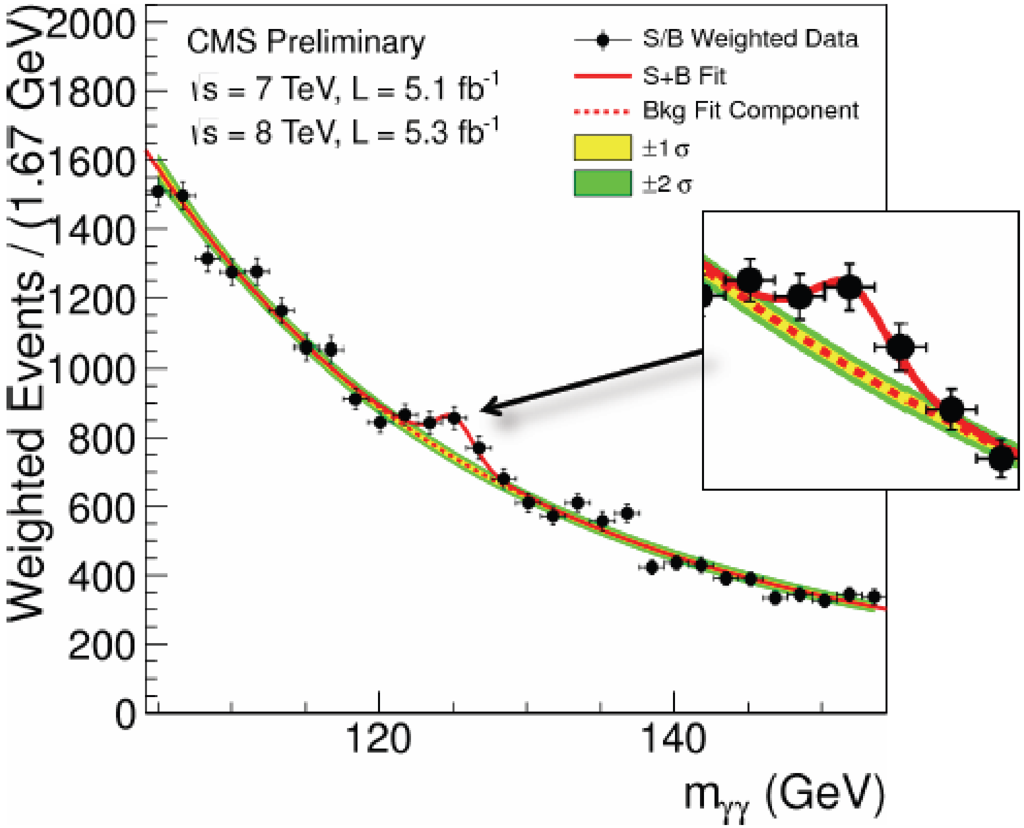
4 July 2012 :
discovery of higgs-like boson





S/B Weighted Mass Distribution

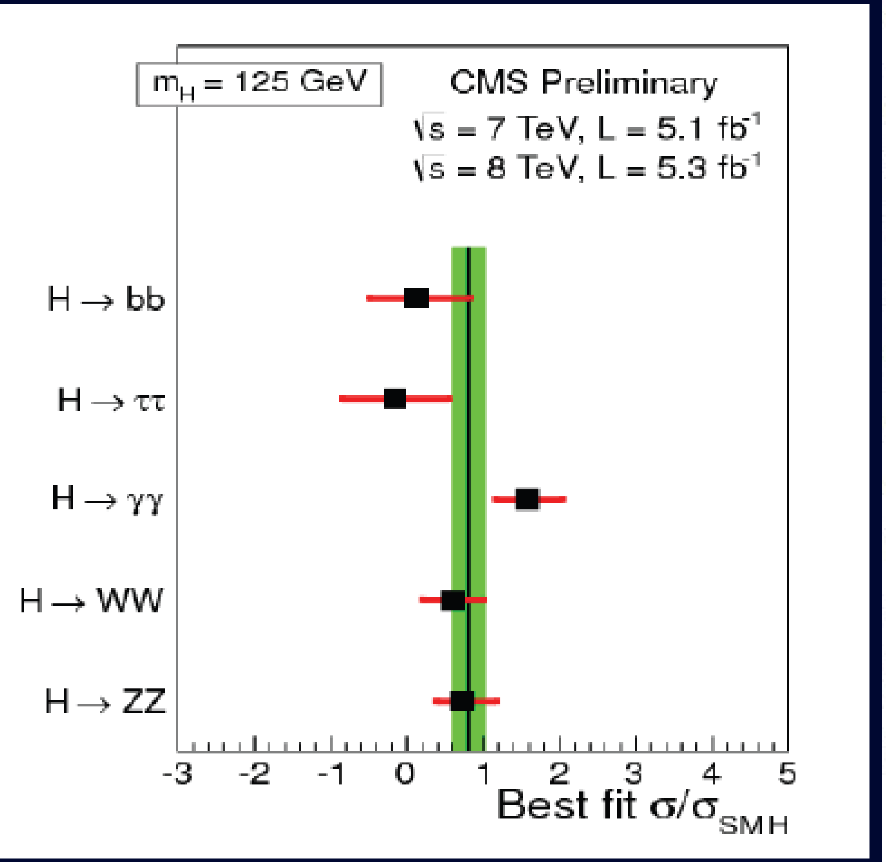
- Sum of mass distributions for each event class, weighted by S/B
  - B is integral of background model over a constant signal fraction interval

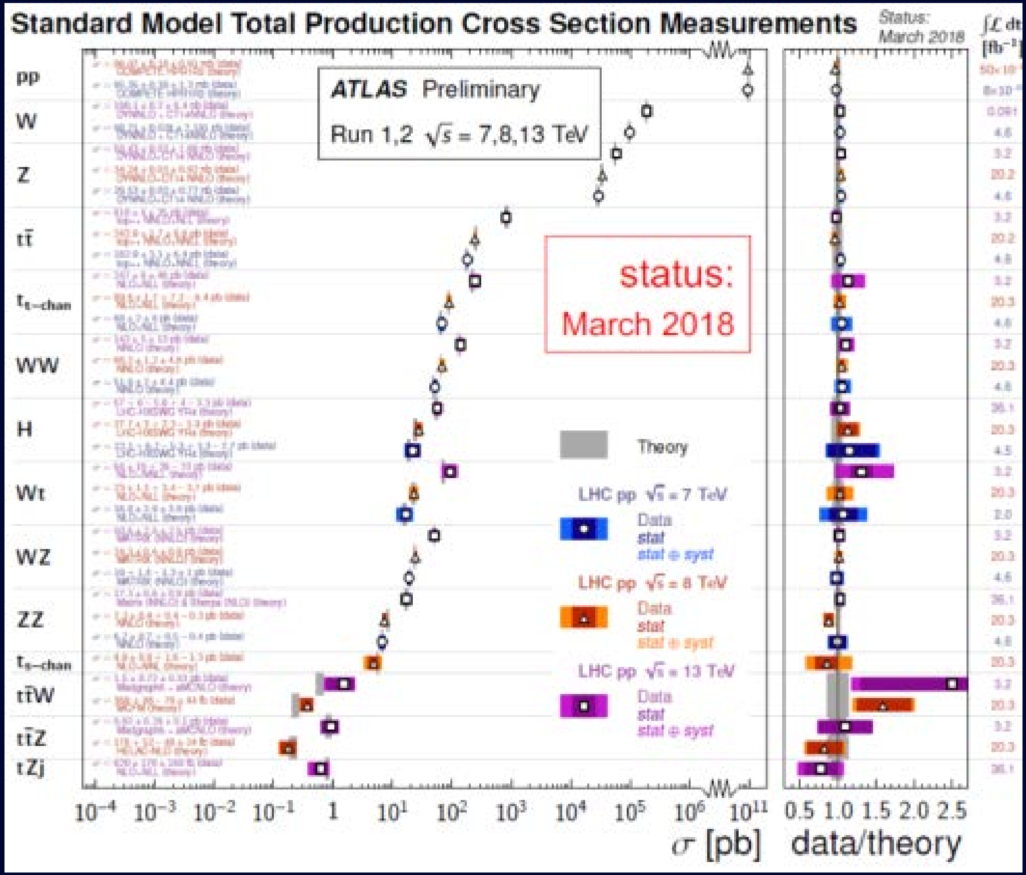


July 4th 2012 The Status of the Higgs Search J. Incandela for the CMS COLLABORATION

43

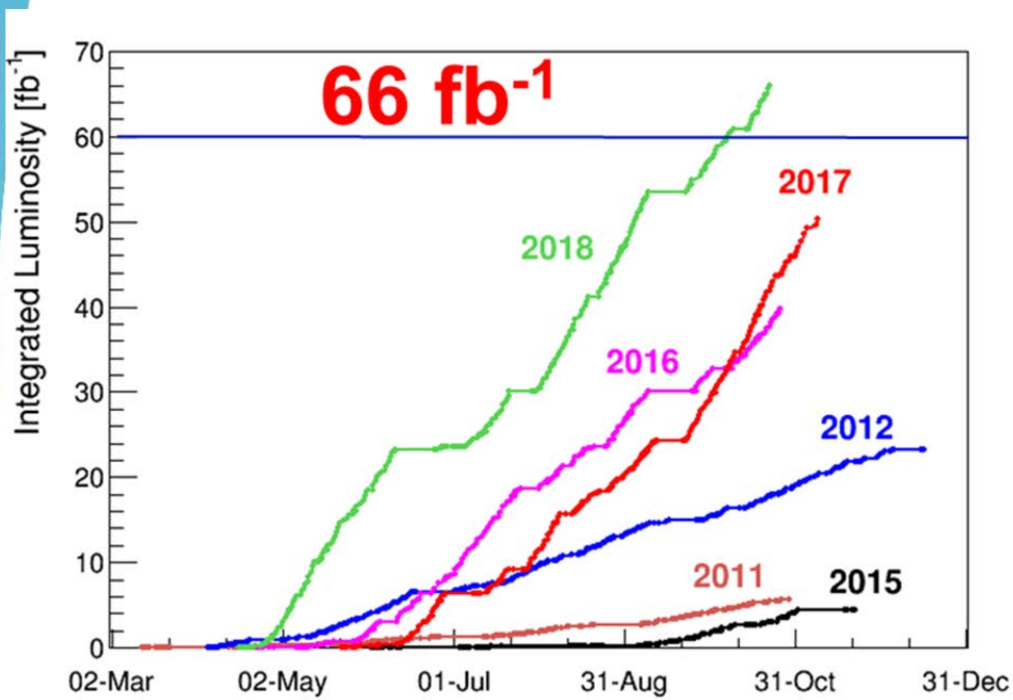
… but that's only the beginning !
What's next ?

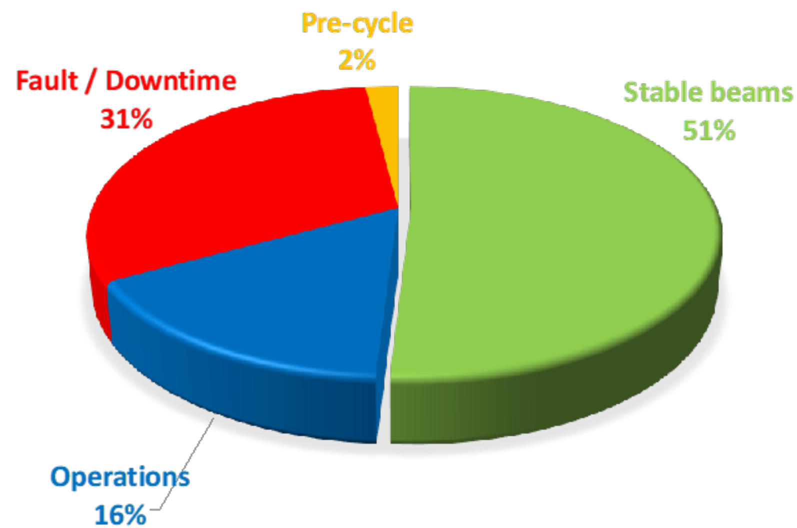




Measure the properties of the new particle
with high precision

LHC today

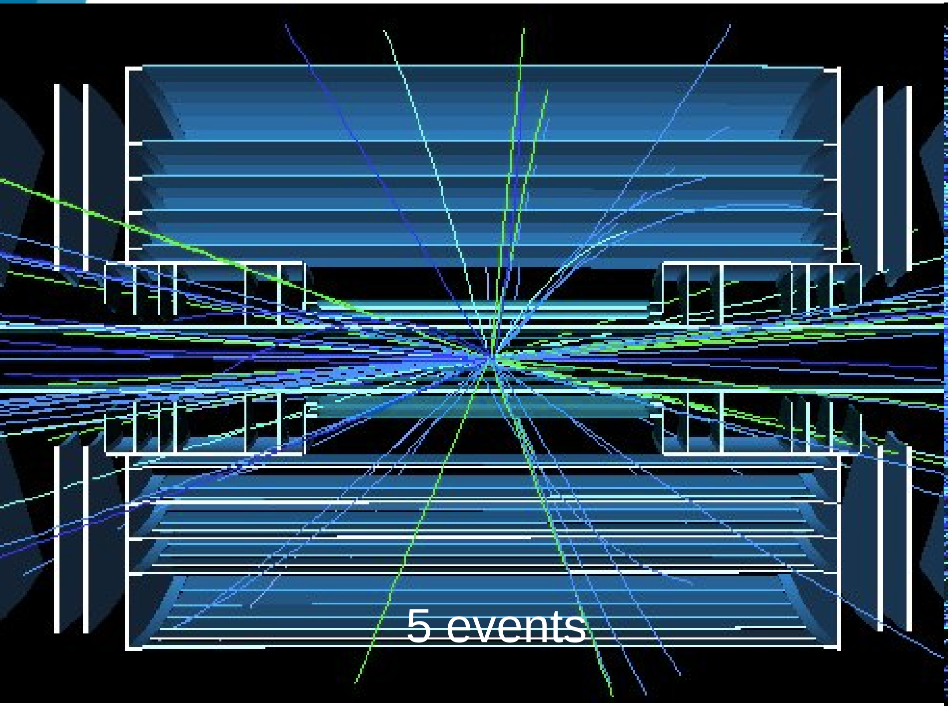


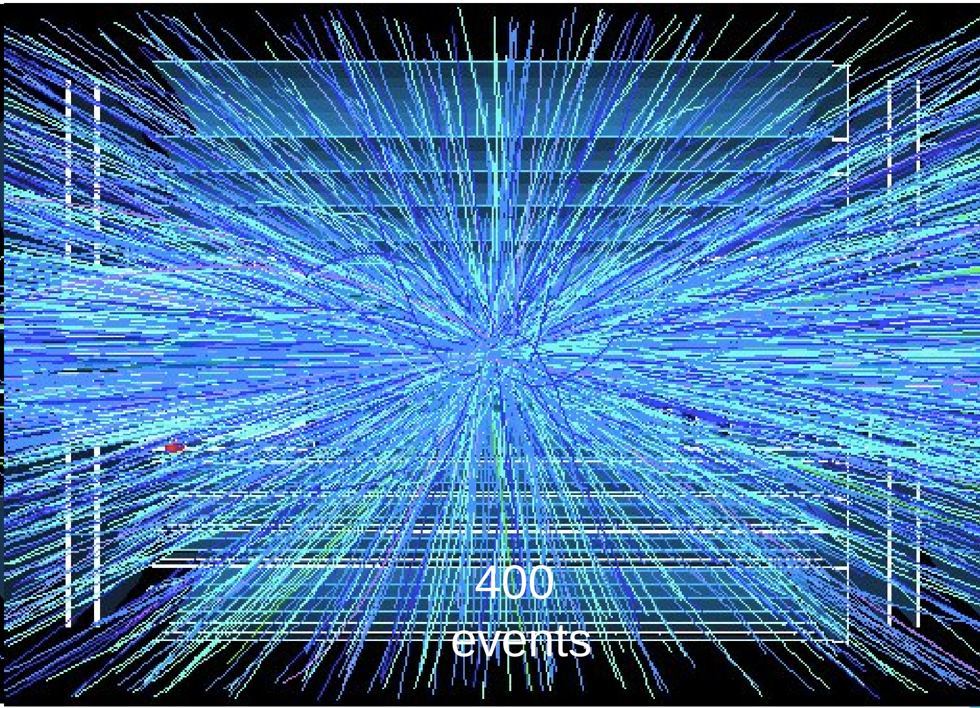


Period	Int. Luminosity [fb^{-1}]
Run 1	29.2
Run 2: 2015	4.2
Run 2: 2016	39.7
Run 2: 2017	50.2
Run 2: 2018	66.0
Total Run1 + Run 2	189.3

Goal of Run1+Run2 was 150 fb^{-1}!

Goal of High Luminosity LHC (HL-LHC):





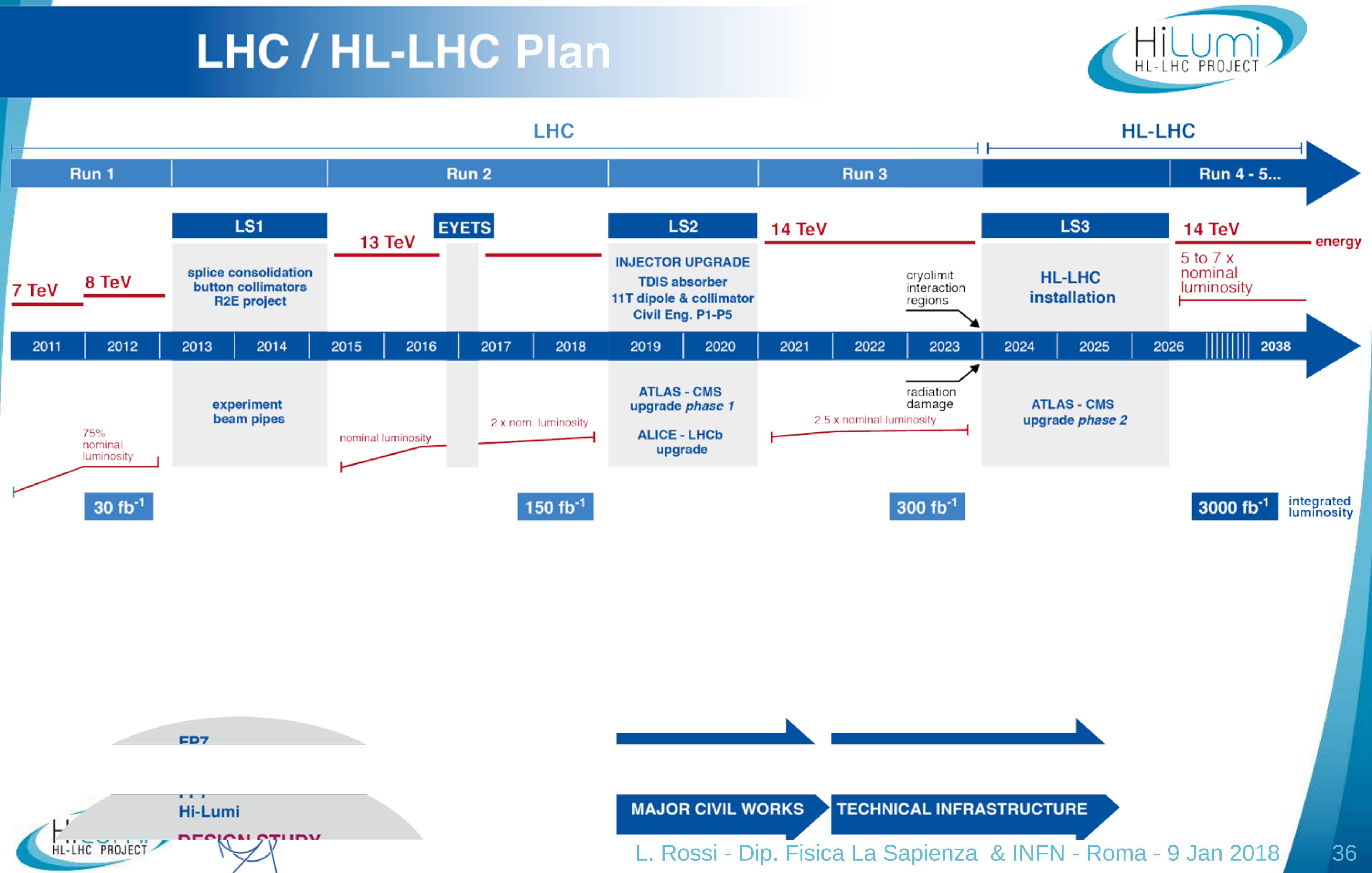
implying an integrated luminosity of **250 fb^{-1} per year**,

design oper. for **μ ~ 140** (➔ peak luminosity **5 10^{34} cm^{-2} s^{-1}**)

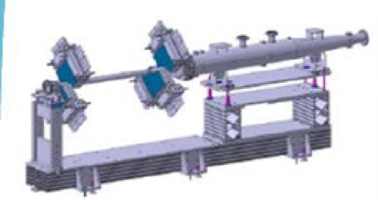
➔ Operation with levelled luminosity!

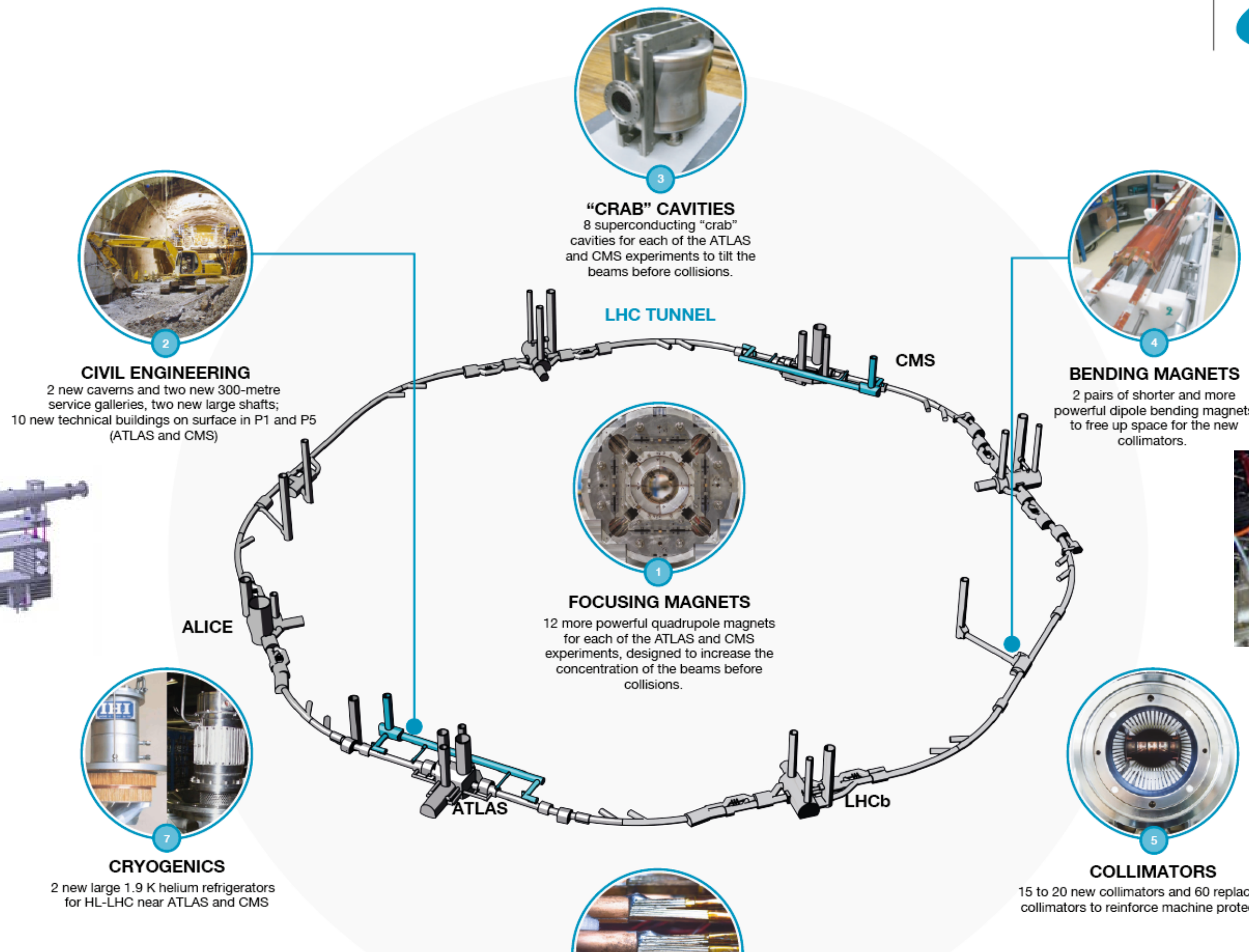
➔ 10x the luminosity reach of first 10 years of LHC operation!!

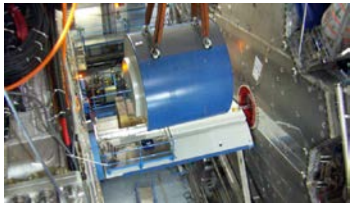
High Luminosity: a luminous future for LHC!

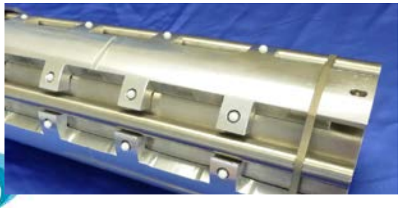


HL-LHC: Pushing the technology!







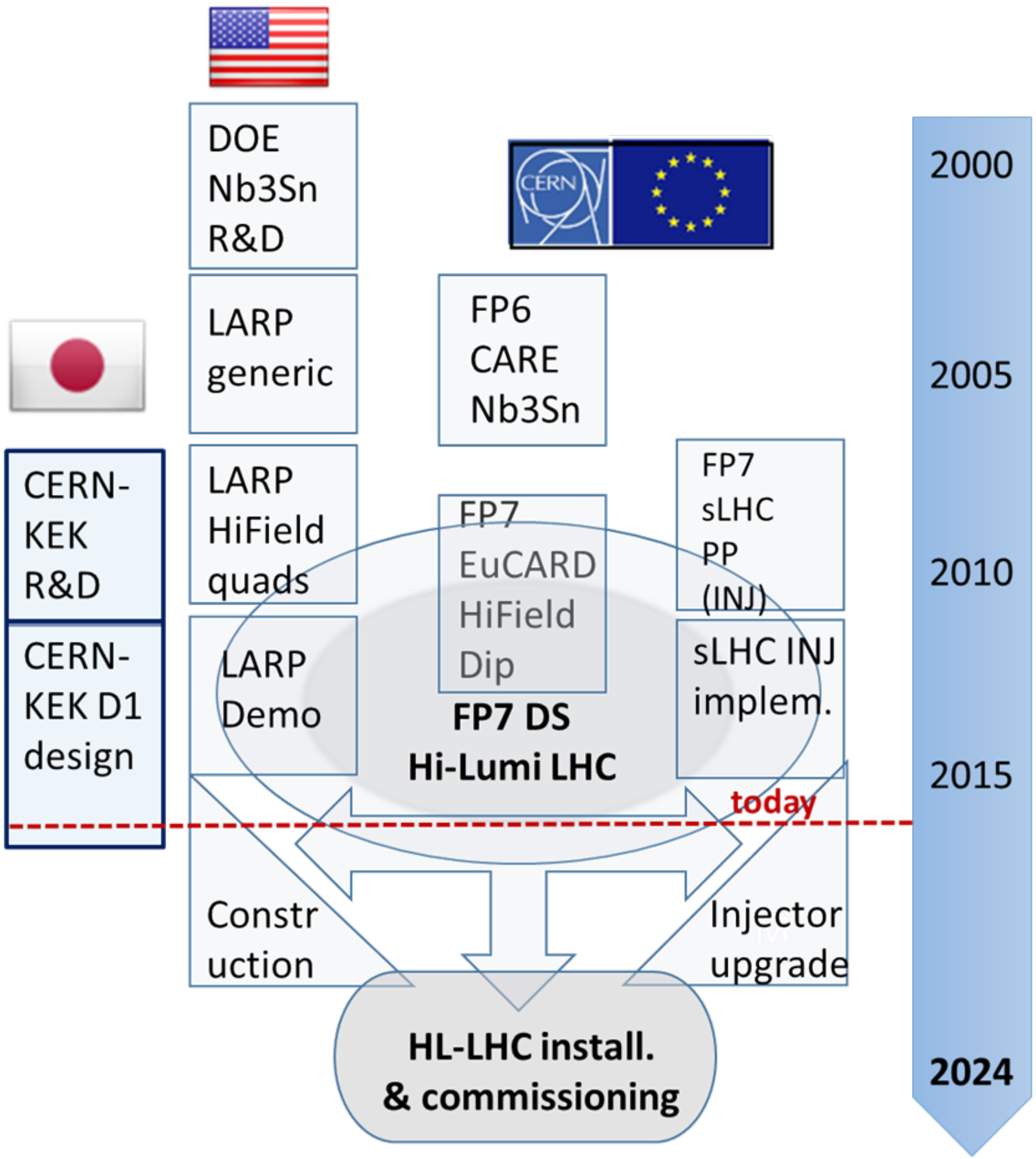


HiLumi LHC: An international collaboration

US-DOE and JP-KEK are the biggest contributor (after CERN and Member States)

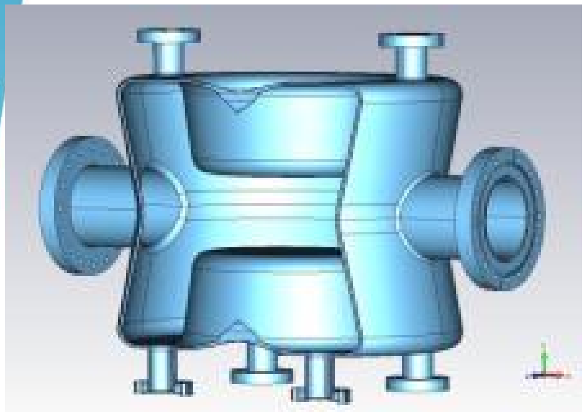
Special in-kind from:
ES – CIEMAT
IT – INFN
SE – Uppsala
UK – STFC & C.I. Univ.

Canada/Triumf
China/IHEP
Russia/BINP

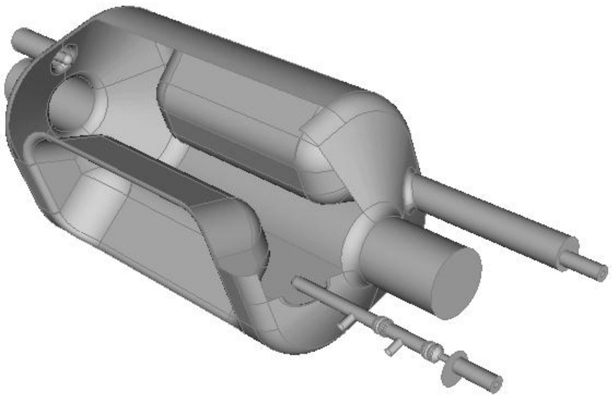


Prototypes built for the three candidates (CERN-UK-USLARP Collaboration)

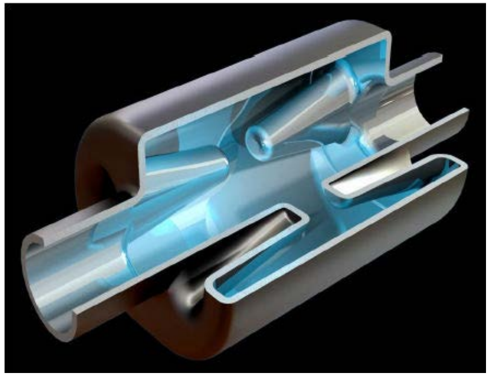
USLARP-BNL



USLARP-ODU/SLAC



UK-Cockcroft/Lancaster U



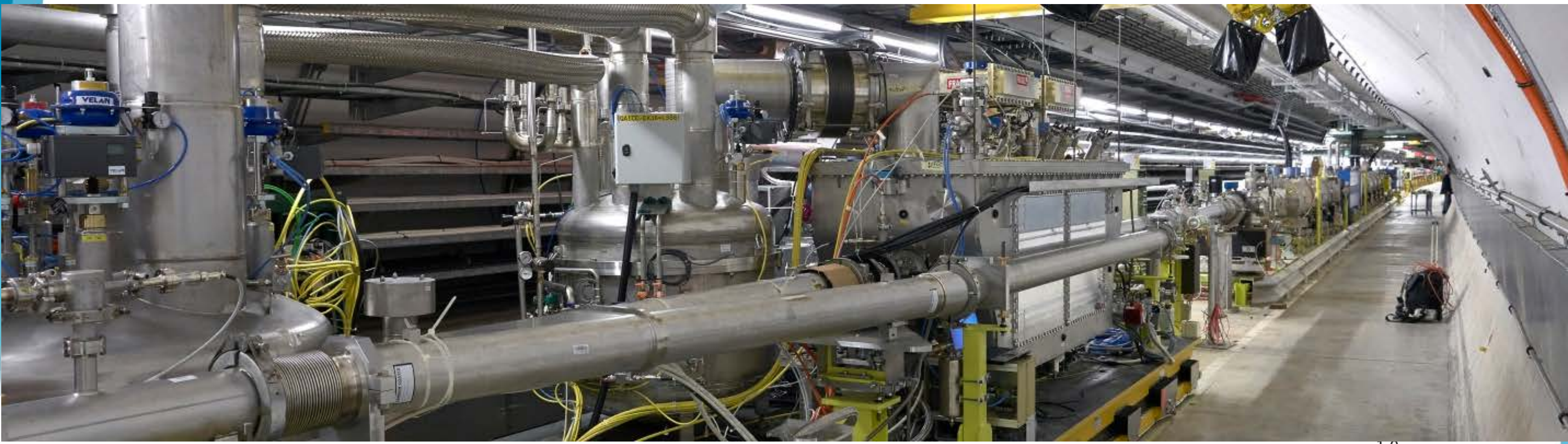
Crab Cavity consruction for SPS test at CERN (DQW type)

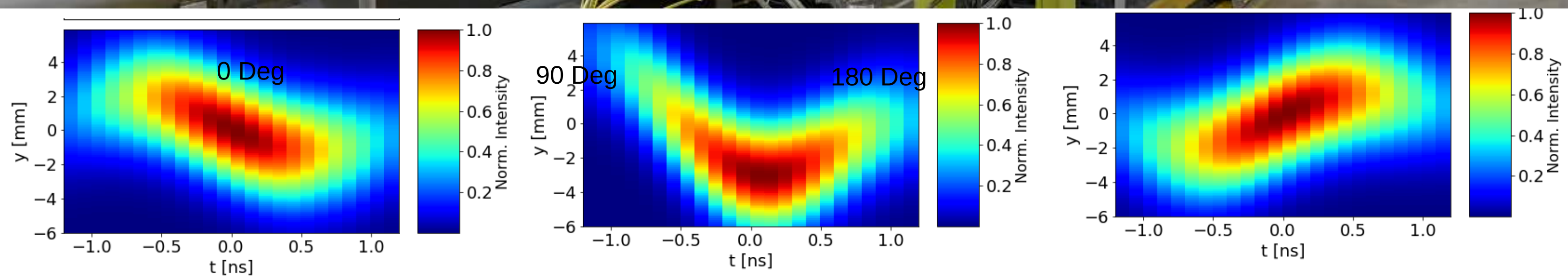
FPC on in Conditioning
Test box & installation of DT

FPC installation onto cavity

String assembly completed
Aug 18, 2017

CC in the SPS: First proton crabbing ever!

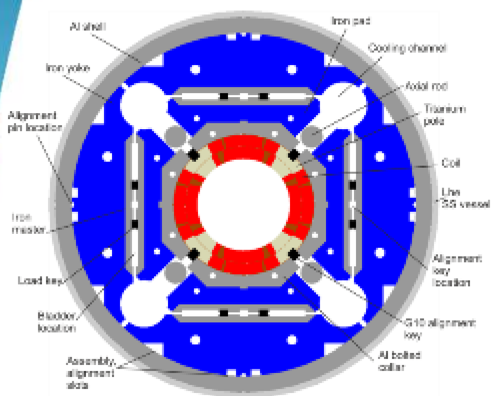




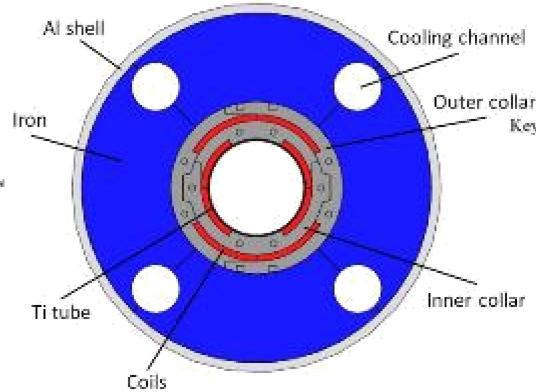
RF phase scan w.r.t the beam phase with cavity 1: principle validated!
Transparency of CC to beam demonstrated! MDs very successful (with E limitation).

μtreatment of km long surface

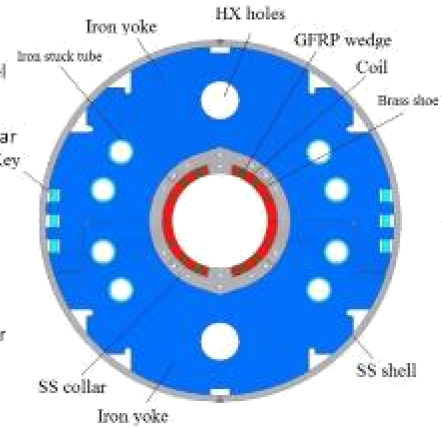
HL-LHC magnet "zoo"



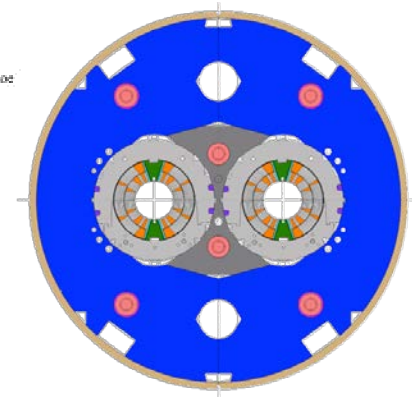
Triplet QXF (LARP and CERN)



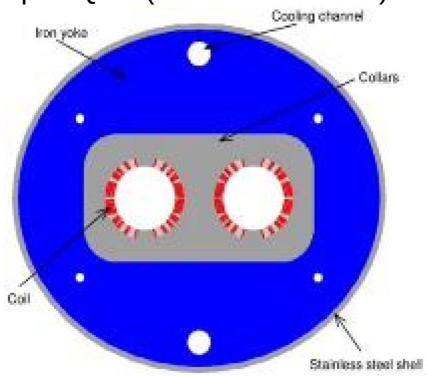
Orbit corrector (CIEMAT)



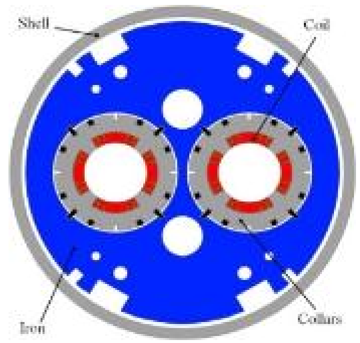
Separation dipole D1 (KEK)



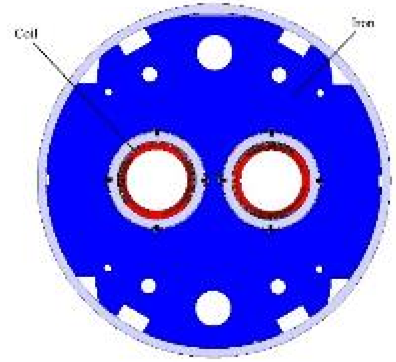
11 T dipole (CERN)



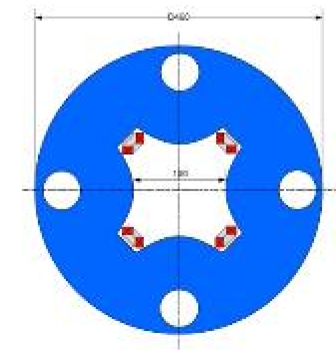
Recombination dipole D2 (INFN)



Q4 (CEA)

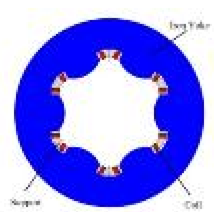


D2/Q4 orbit corrector (CERN)

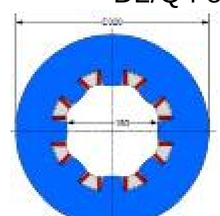


Skew quadrupole (INFN)

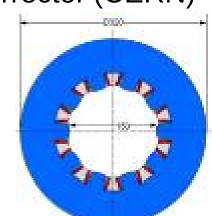
Approximately 150 single magnets and 50 cold masses for HL-LHC



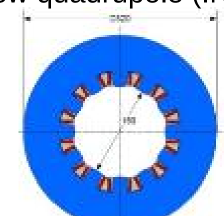
Sextupole (INFN)



Octupole (INFN)

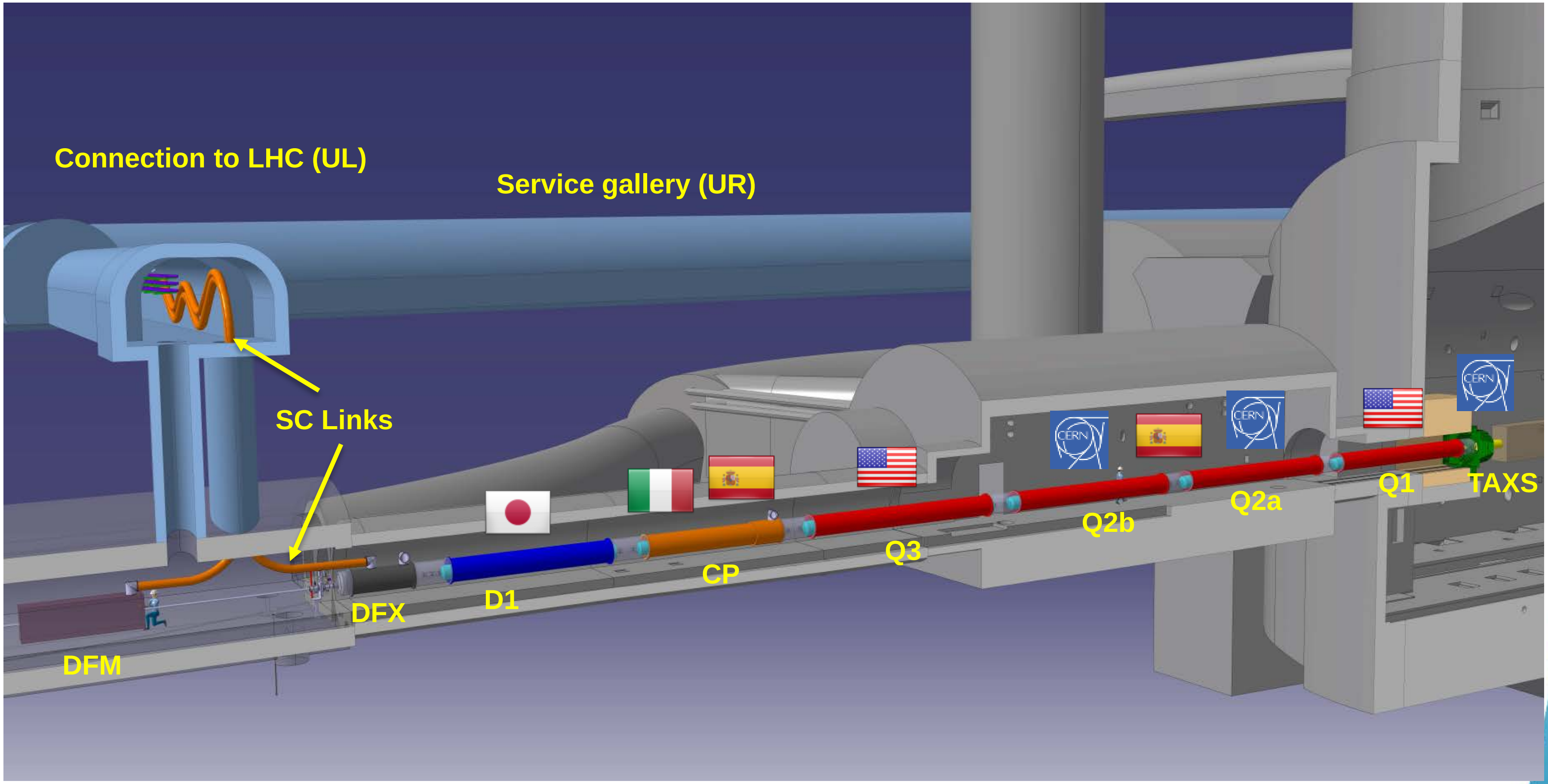


Decapole (INFN)

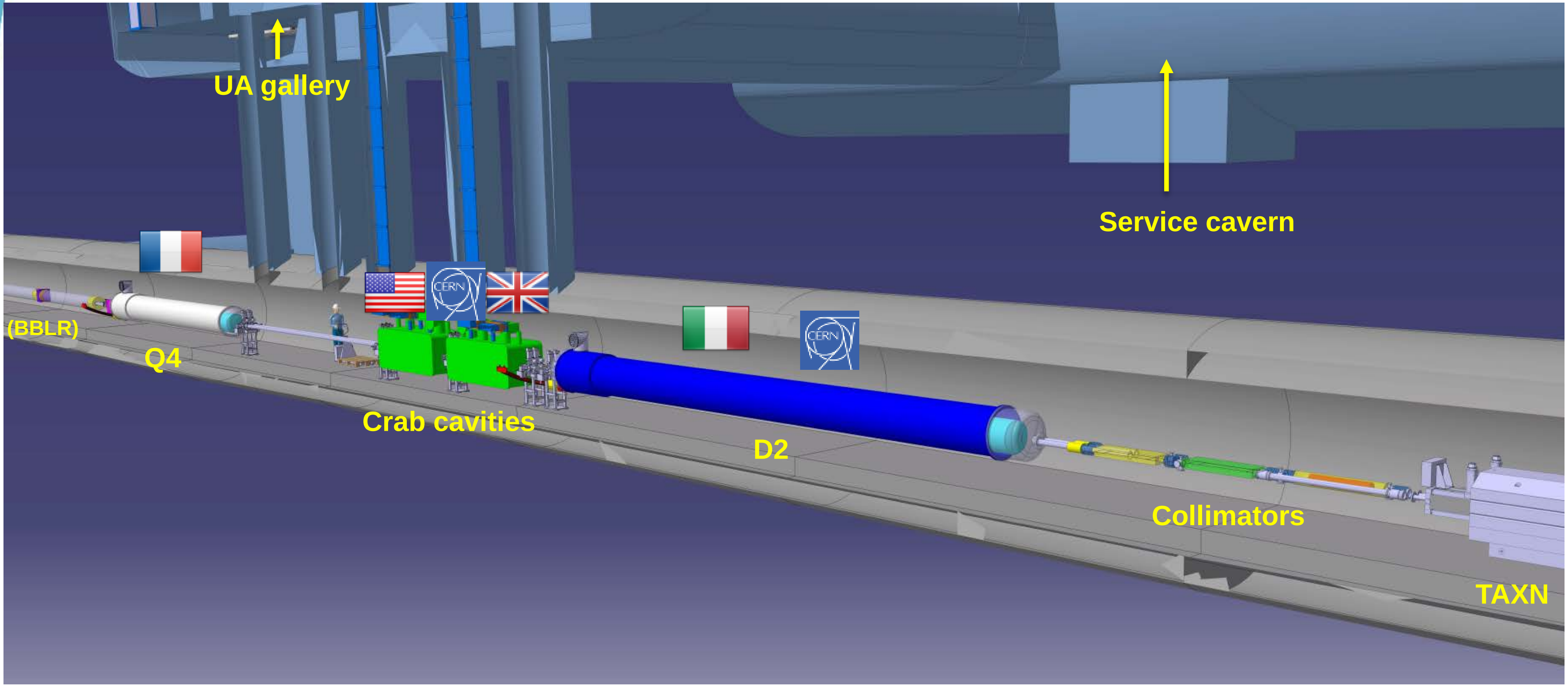


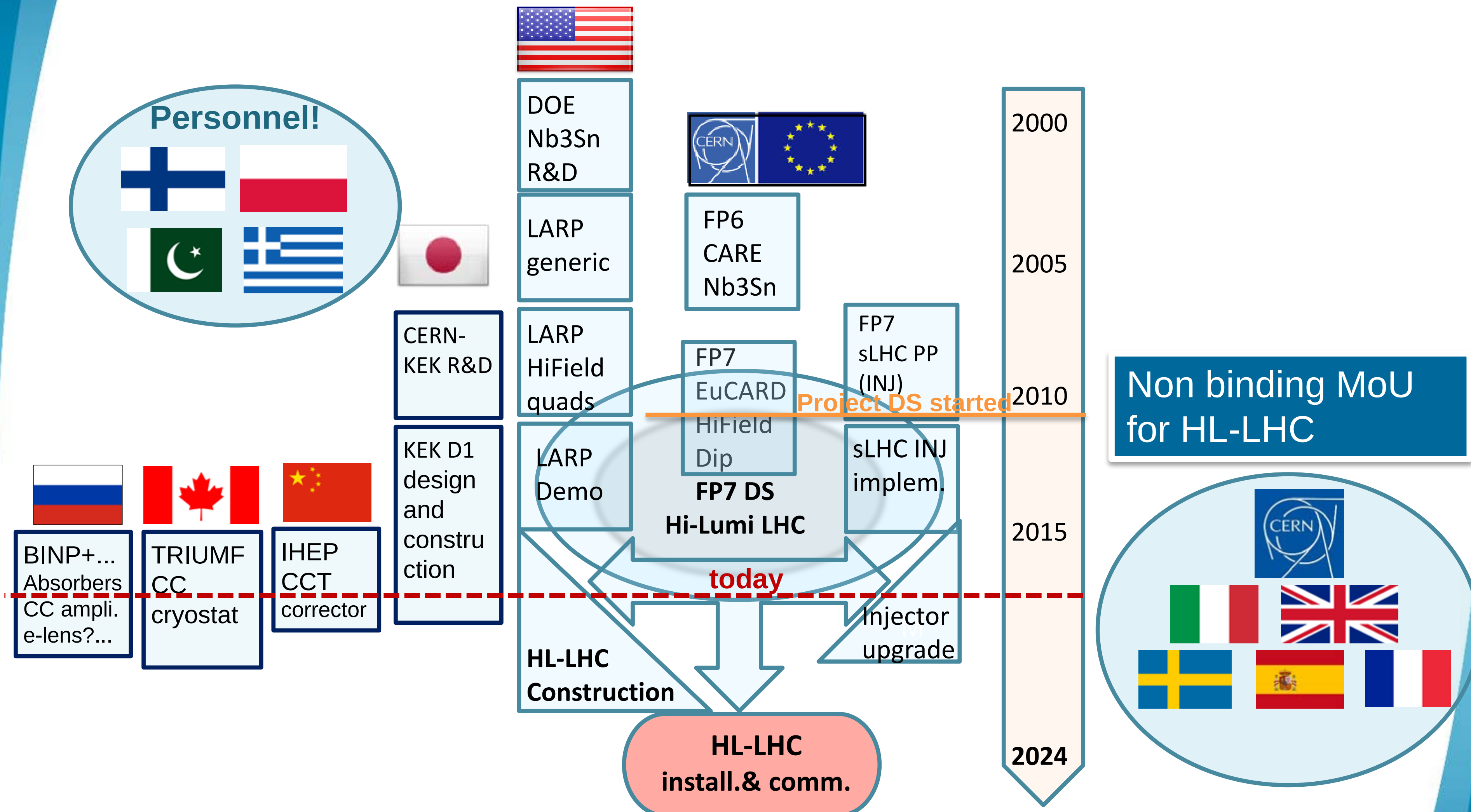
Dodecapole (INFN)

High Luminosity LHC -1 New Triplets IT QUADs



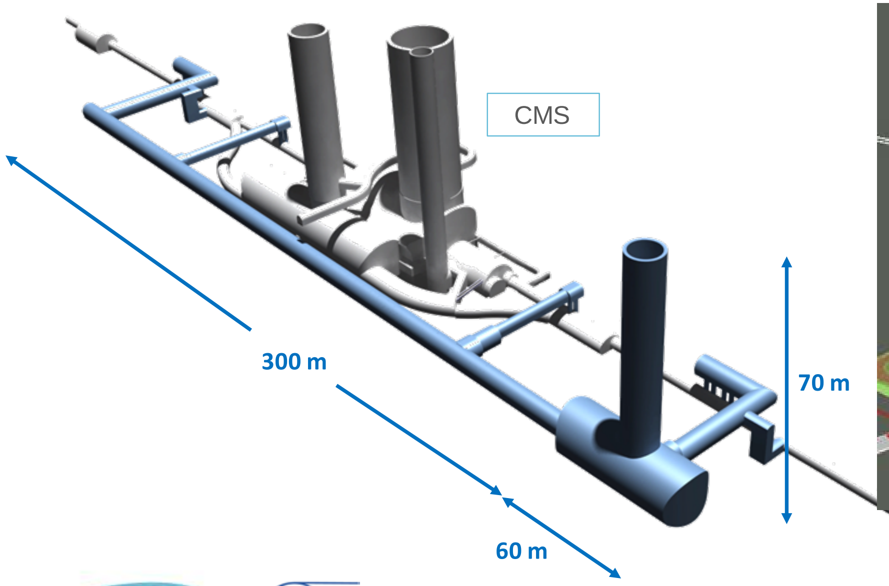
High Luminosity LHC – 2 New Matching section




Personnel!
DOE Nb3Sn R&D
LARP generic
LARP HiField quads
LARP Demo
CERN-KEK R&D
KEK D1 design and constru ction
FP6 CARE Nb3Sn
FP7 EuCARD HiField Dip
FP7 sLHC PP (INJ)
Project DS started
sLHC INJ implem.
FP7 DS Hi-Lumi LHC
today
Injector upgrade
HL-LHC Construction
HL-LHC install.& comm.
BINP+... Absorbers CC ampli. e-lens?...
TRIUMF CC cryostat
IHEP CCT corrector
2000
2005
2010
2015
2024
Non binding MoU for HL-LHC

WP17 (C.E. and Tech. Infr.) Status

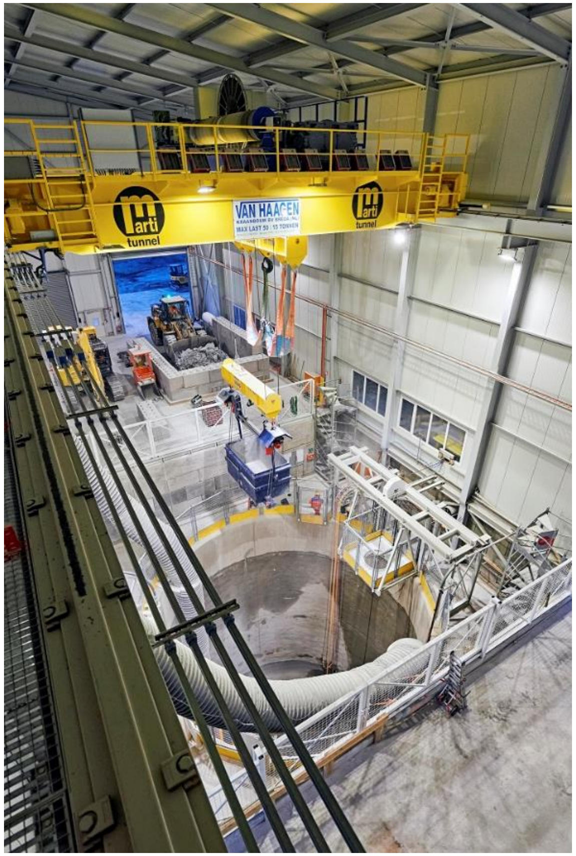
- WP17.1: Civil engineering
  - Preliminary design completed in December 2016
  - Tendering design and contractual documents issued on July 2017 !
  - **Two main contracts (one for Point 1 and another one for Point 5) Awared and signed in March 2018!**

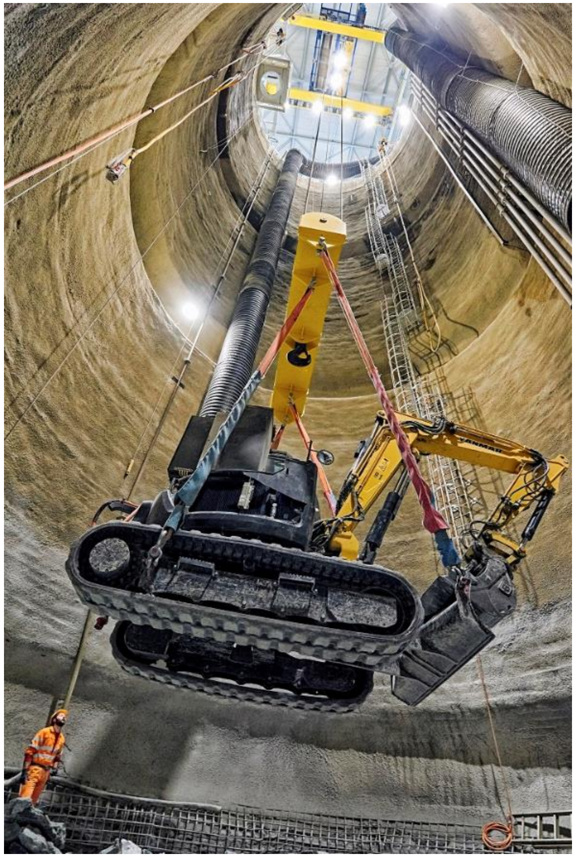


15 June 2015 : HiLumi LHC Groudbreaking Ceremony

Contract T117 – JVMM – LHC P1 (ATLAS)

Contract T117 – JVMM – LHC P1 (ATLAS)





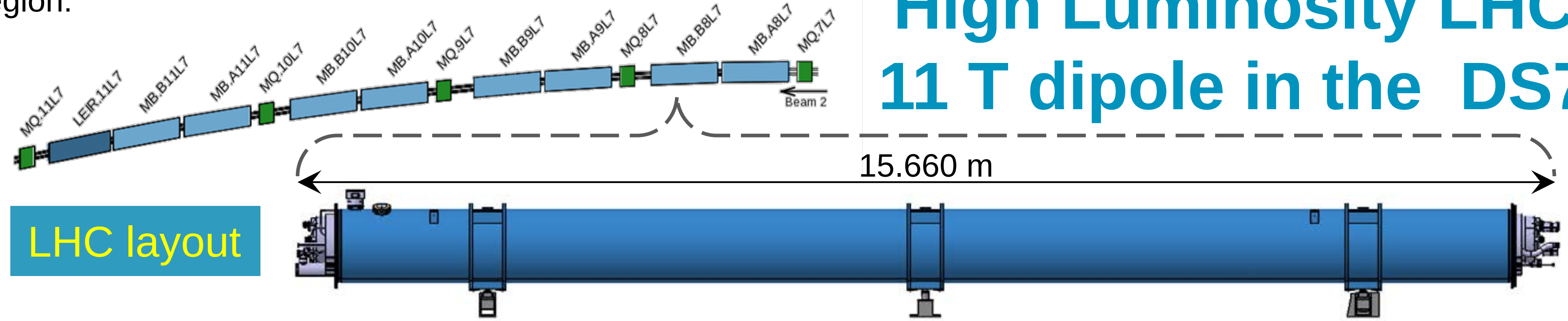
Contract T117 – JVMM – LHC P1 (ATLAS)

Contract T118 – CIB – LHC P5 (CMS)

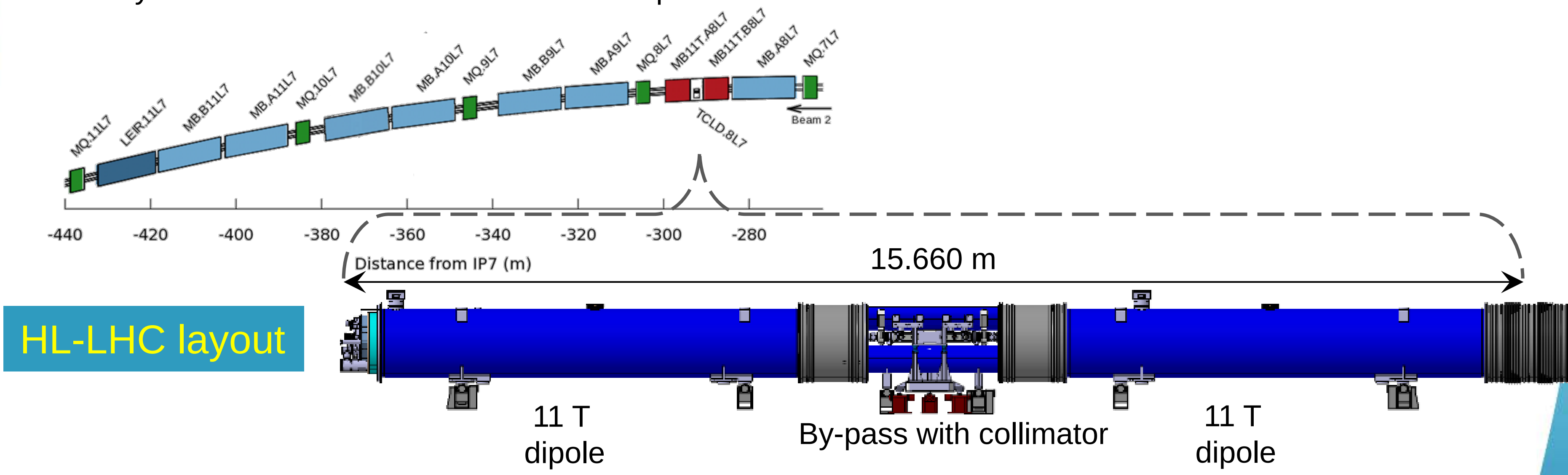
Contract T118 – CIB – LHC P5 (CMS)

High Luminosity LHC
11 T dipole in the DS7

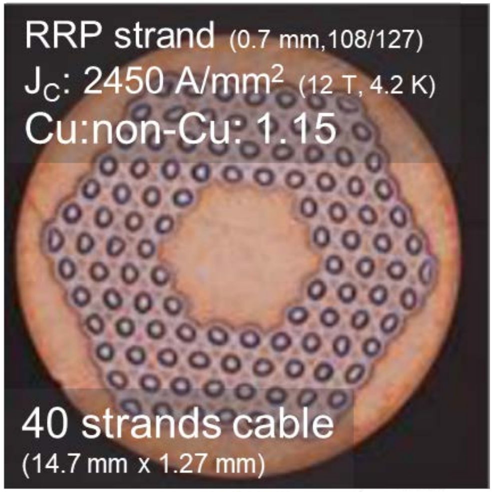
Present layout of the DS region:

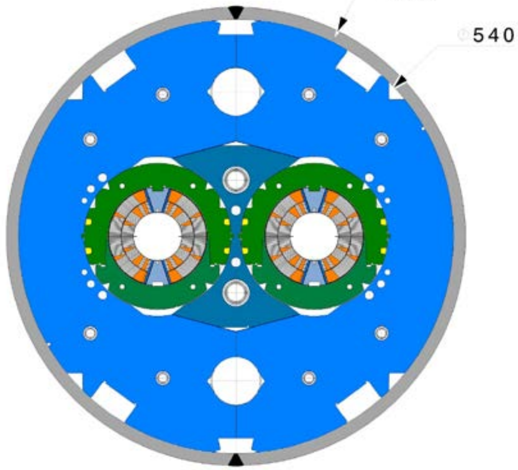


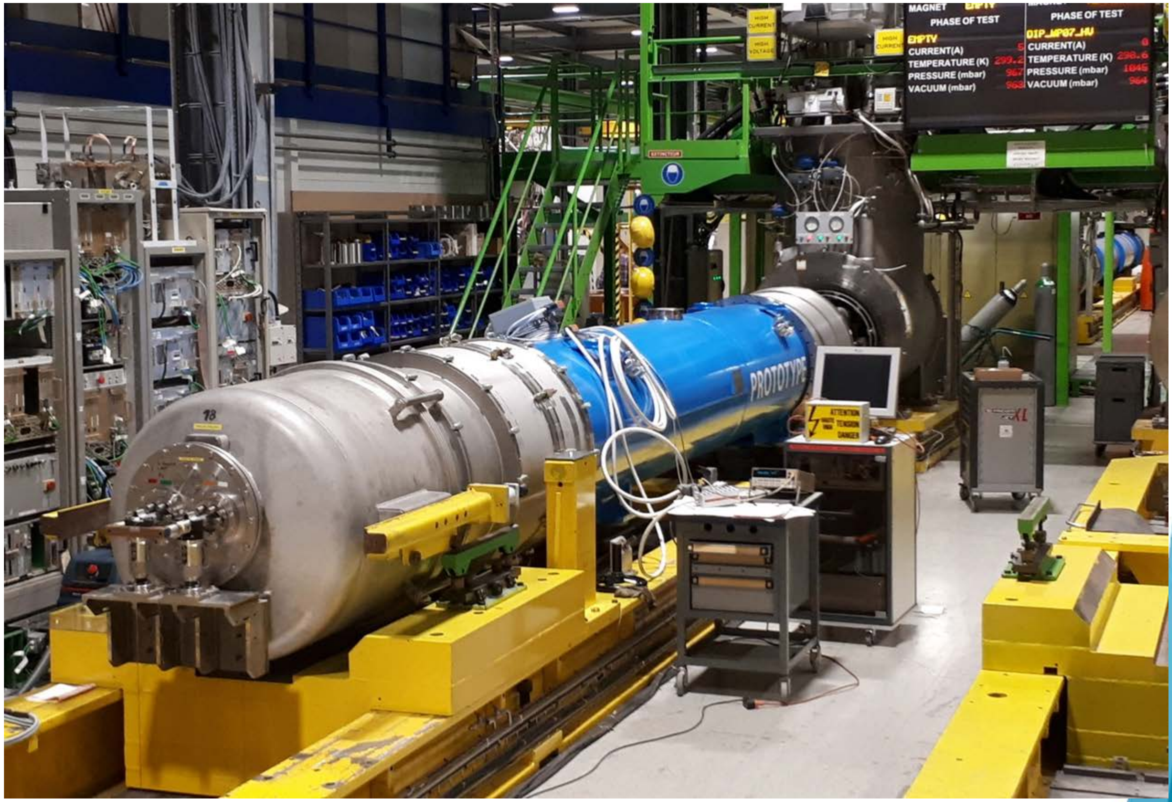
New layout with one collimator and two 11T dipoles:



First 11 T prototype (full size) on test @ CERN



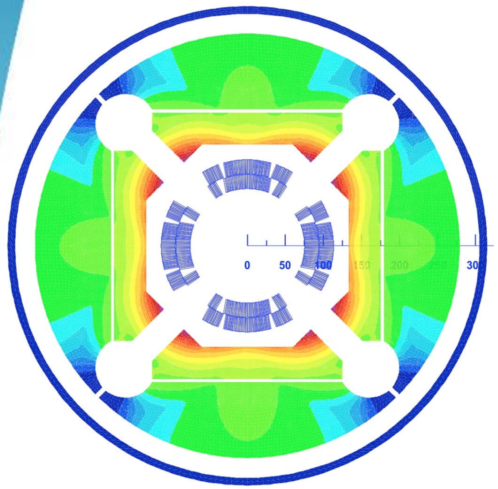


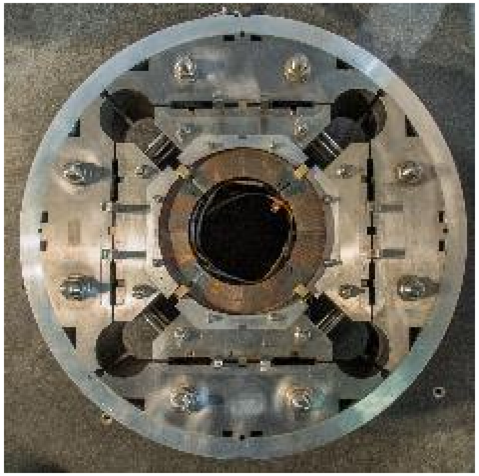


Result not positive (<10 T) - Magnet under rework to test second aperture alone

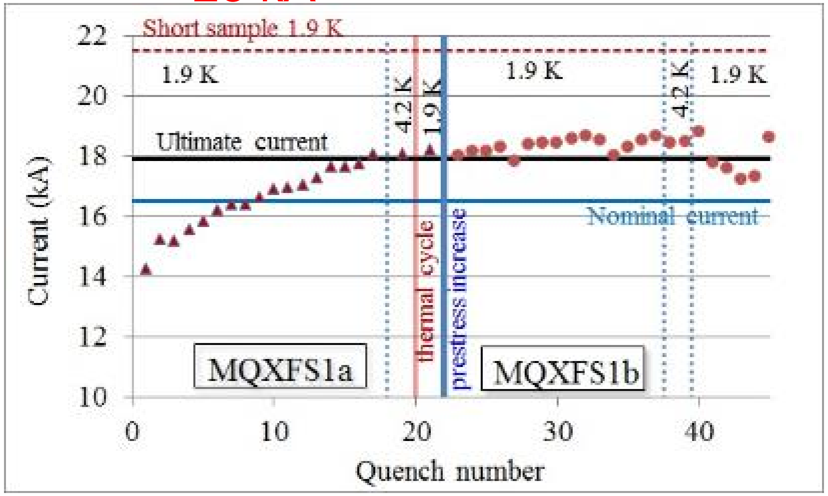
11T production

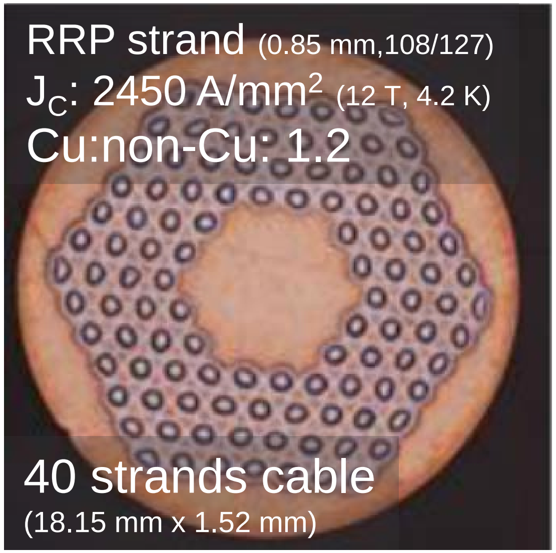
MQXFS1 results

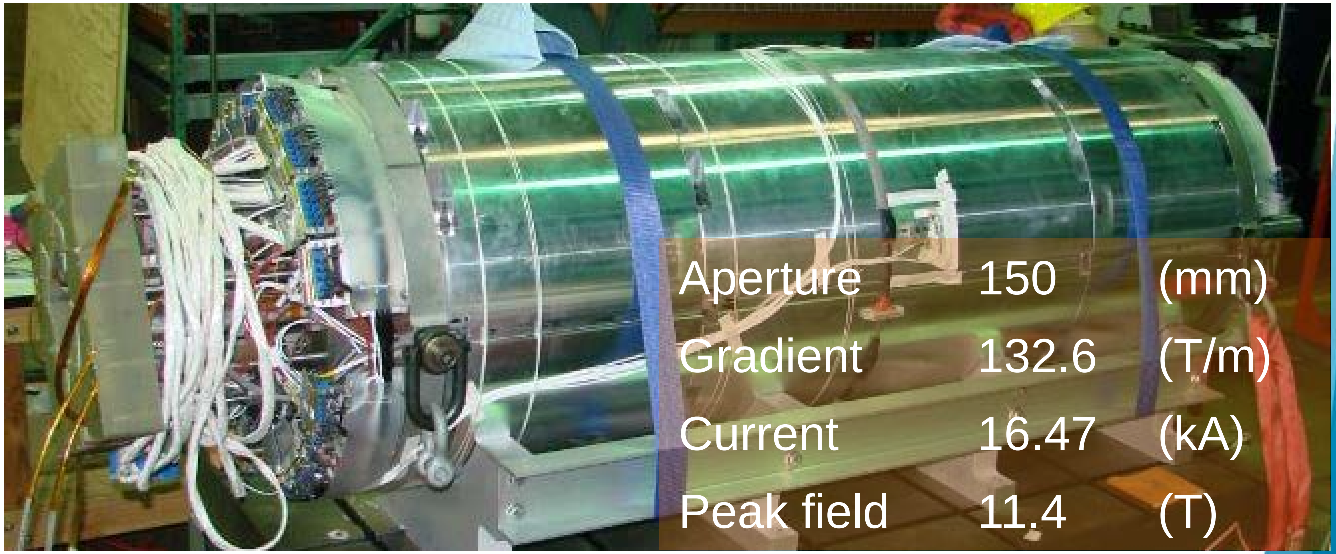




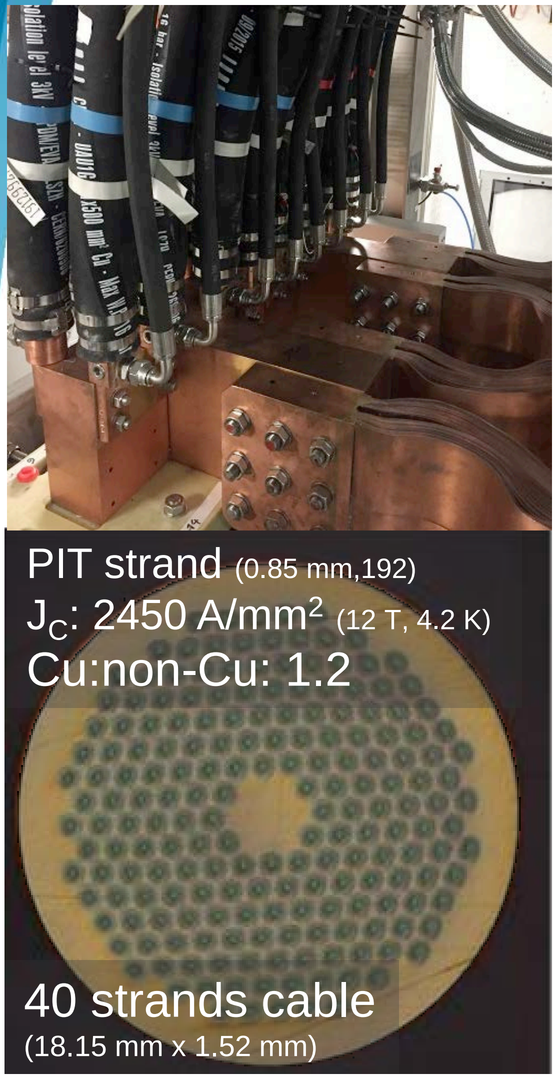
≈ 28 kA





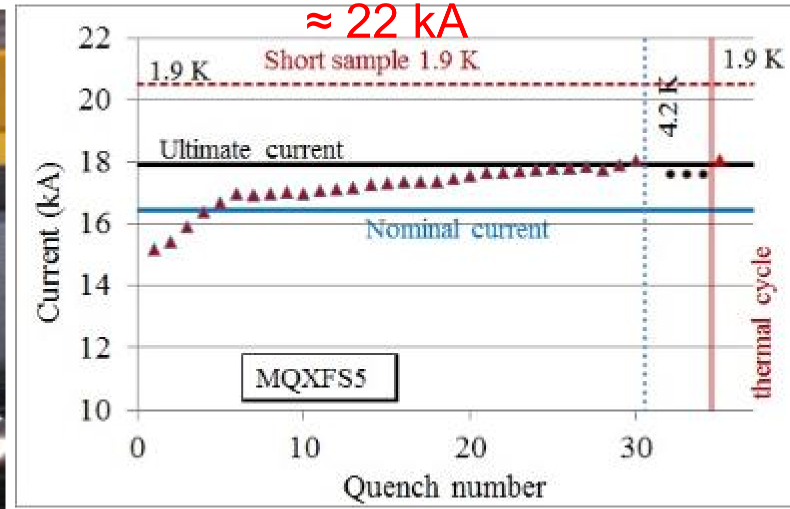


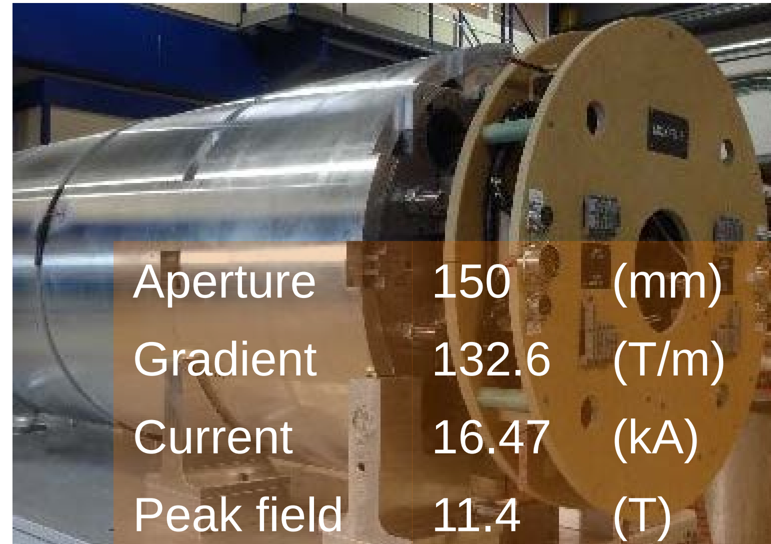
MQXFS5 results



PIT strand (0.85 mm,192)
J_C: 2450 A/mm^2 (12 T, 4.2 K)
Cu:non-Cu: 1.2

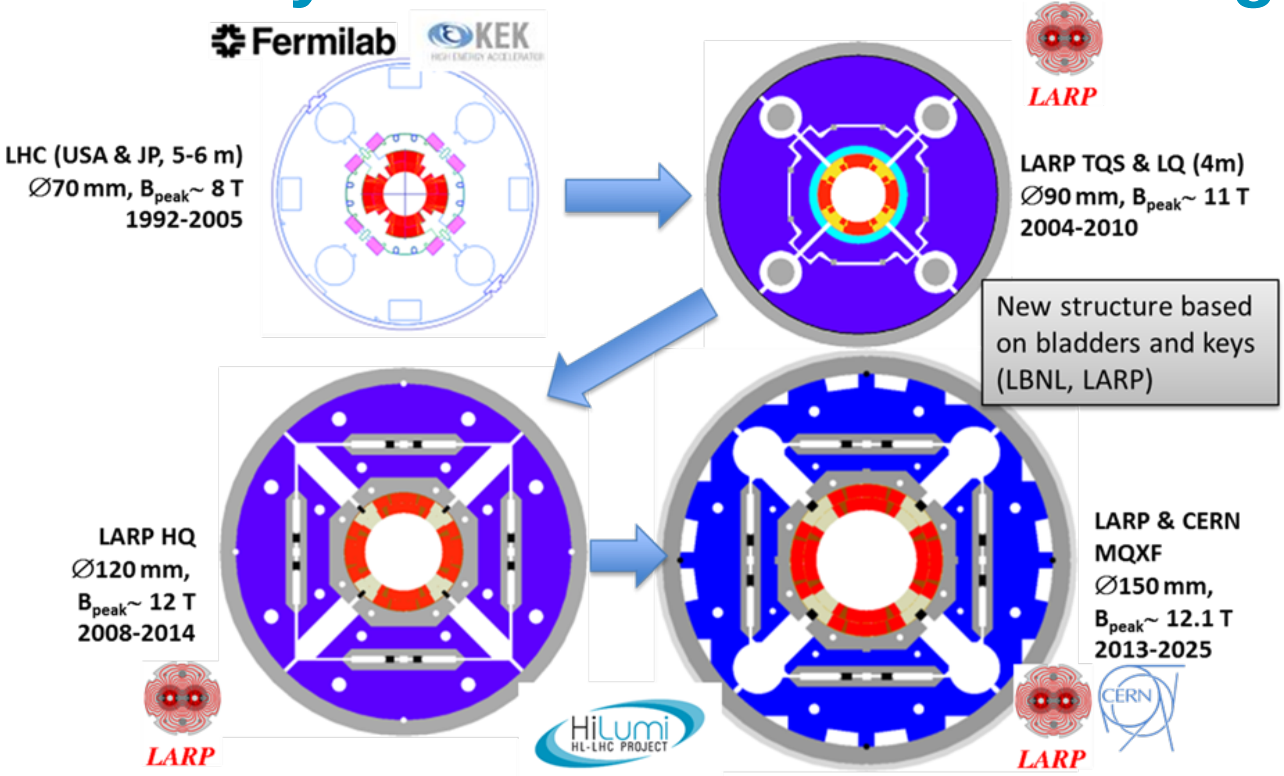
40 strands cable
(18.15 mm x 1.52 mm)



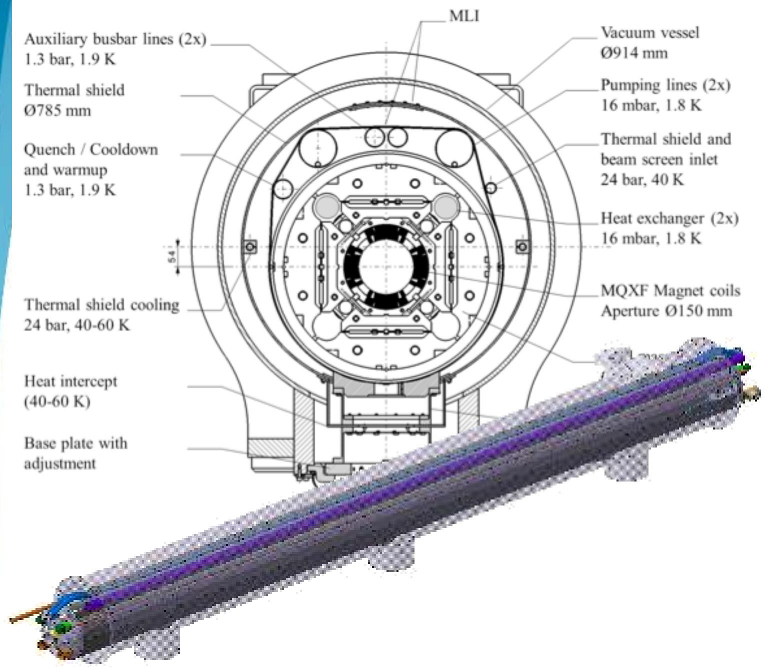


Aperture	150	(mm)
Gradient	132.6	(T/m)
Current	16.47	(kA)
Peak field	11.4	(T)

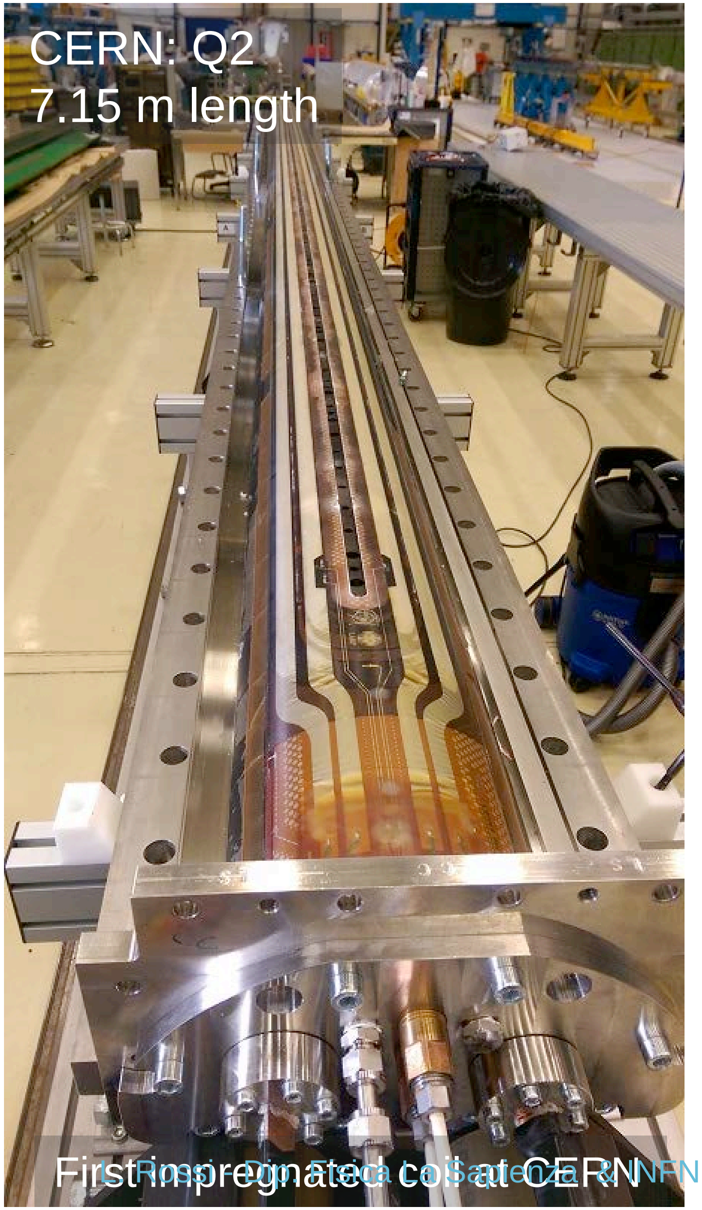
IT quadrupole. Increase in field but also in size wrt LHC. Very relevant also for FCC magnets



LQXF production




Coil winding at CERN


CERN: Q2
7.15 m length

First impregnated coil at CERN


US: Q1/Q3
4.2 m length

Long mirror test at BNL

2016 Full approval of HL-LHC by Council
2016 HL-LHC new ESFRI landmark (right)

The High-Luminosity LHC Project

Abstract

The scientific case for a luminosity upgrade of the Large Hadron Collider (High-Luminosity LHC, HL-LHC) is presented. It includes measurements of the Higgs boson properties with unprecedented precision and increased potential in the search for new physics. Construction is expected to be completed by the mid-twenties, and by the mid-thirties the HL-LHC should have provided a tenfold increase in the integrated luminosities recorded by the experiments. Main upgrade components include new-technology supercoducting magnets and current leads. The cost of the collider upgrade, which will be realised within a constant CERN Budget, is estimated to be 950 MCHF. The main technical challenges, as well as the ongoing R&D work and the main milestones of the implementation plan, are described.

ESFRI ROADMAP 2016

PART 1 PART 2 PART 3 ANNEXES

ESFRI LANDMARKS

PHYSICAL SCIENCES & ENGINEERING

An upgrade of the highest-energy particle collider in the world for exploring new physics

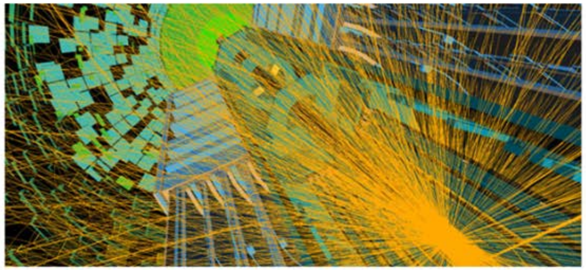
HL-LHC

High-Luminosity Large Hadron Collider

TYPE: single-sited
COORDINATING ENTITY: CERN
MEMBER COUNTRIES: AT, BE, BG, CH, CZ, DE, DK, EL, ES, FI, FR, HU, IL, IT, NL, NO, PK, PL, PT, RO, RS, SE, SK, TR, UK

PARTICIPANTS: See
ACCELERATOR COLLABORATION
ATLAS COLLABORATION
CMS COLLABORATION

TIMELINE
- ESFRI Roadmap entry: 2016
- Preparation phase: 2014-2017
- Construction phase: 2017-2025

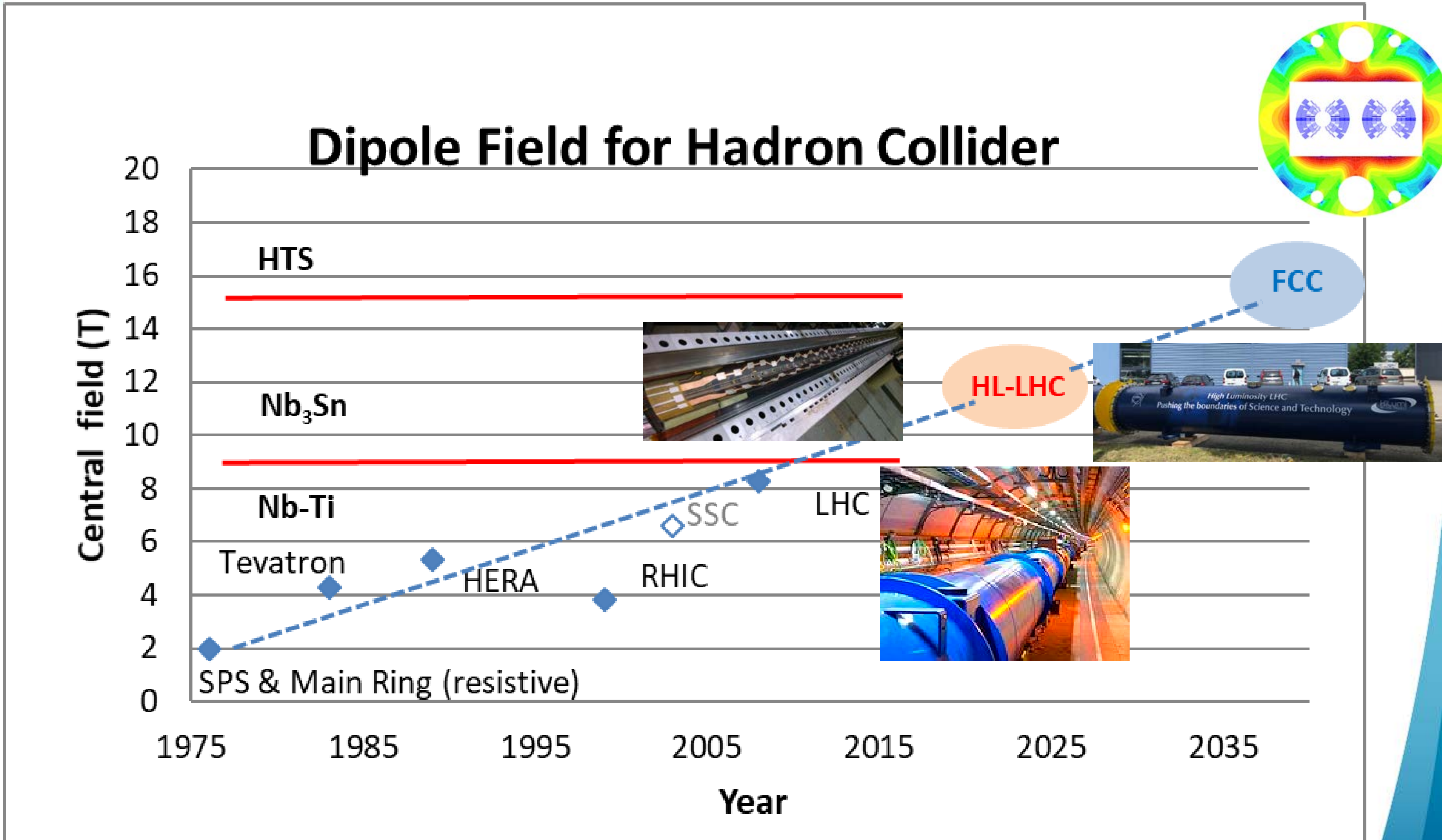


Description

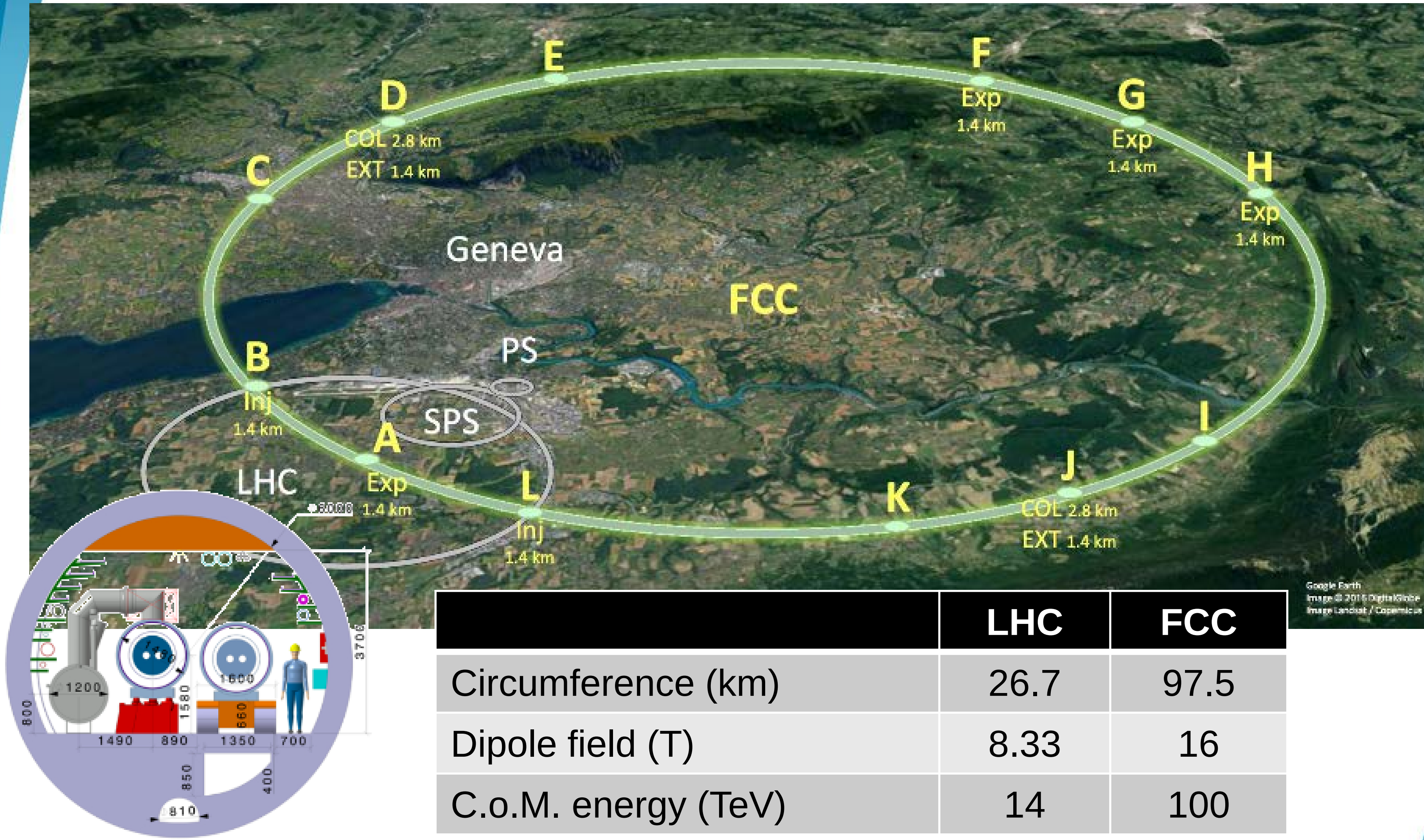
The Large Hadron Collider (LHC) at CERN is the highest-energy particle collider in the world. The ATLAS and CMS experiments at the LHC have provided the breakthrough discovery of the so-called Higgs boson. This discovery is the start of a

The 29 ESFRI Landmarks which have now reached the implementation phase are pan-European hubs of scientific excellence, generating new ideas and pushing the boundaries of science and technology. They are important pillars of European research and innovation for the next decades and they will require continuous support to fulfil their mission and ensure their long-term sustainability.

HiLumi LHC: preparing technology for next big steps



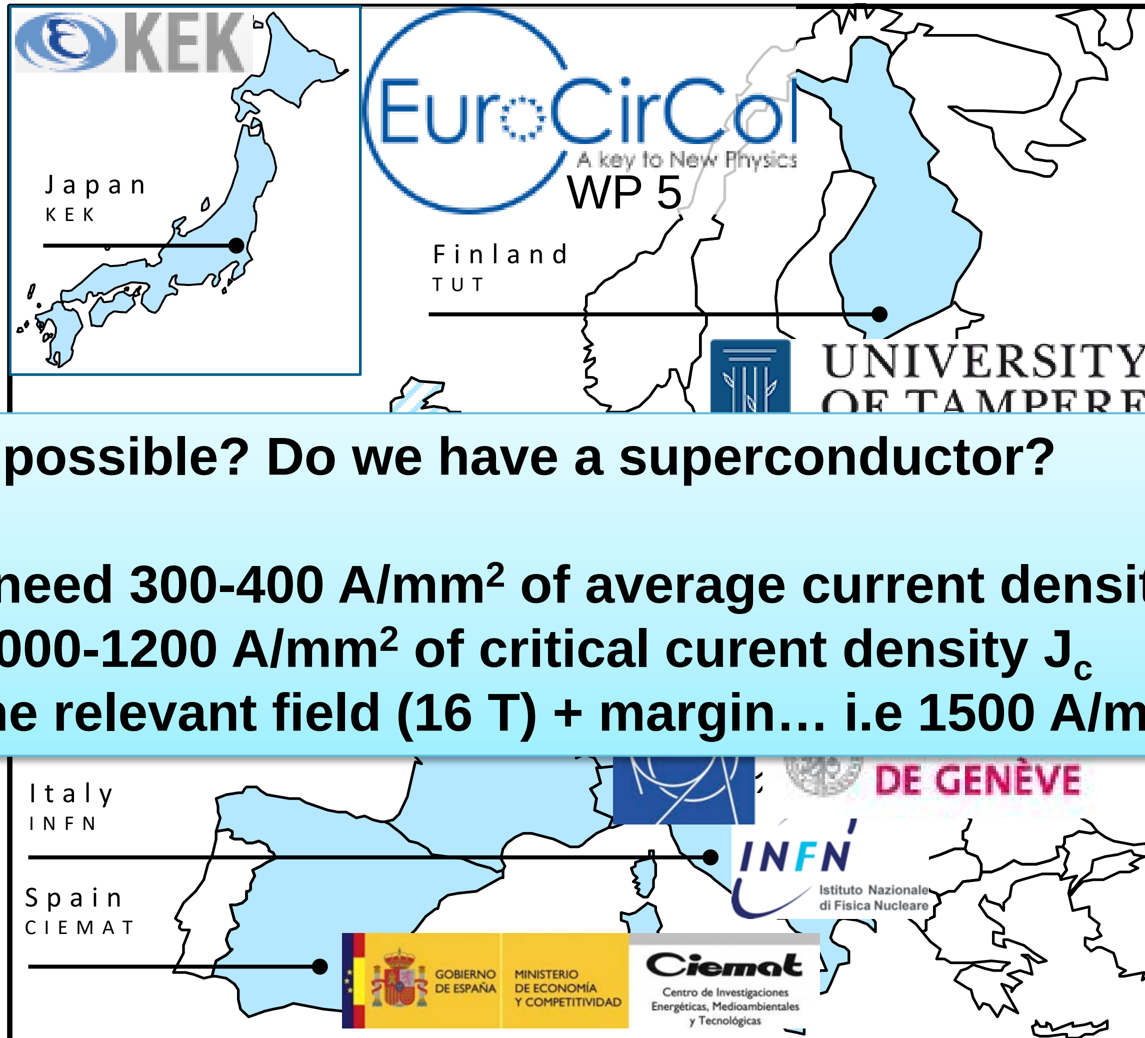
Future Circular Collider



	LHC	FCC
Circumference (km)	26.7	97.5
Dipole field (T)	8.33	16
C.o.M. energy (TeV)	14	100

Courtesy of M. Benedikt, FCC

CERN/EU program for 16 T dipole



Is it possible? Do we have a superconductor?

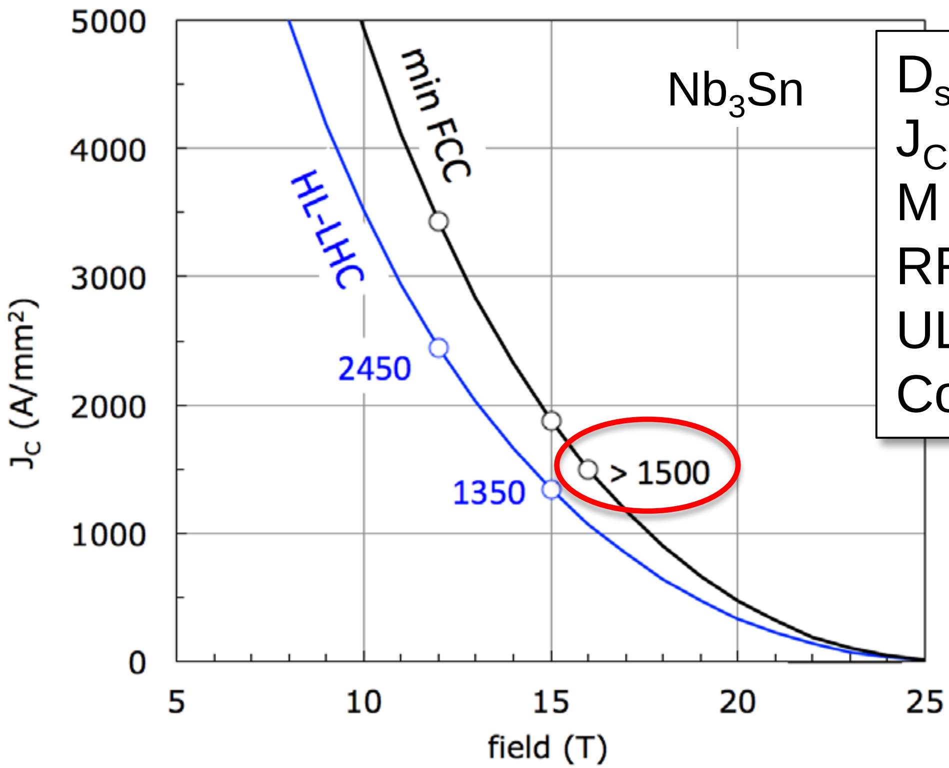
We need 300-400 A/mm² of average current density J_e
$\Rightarrow$ 1000-1200 A/mm² of critical curent density J_c
at the relevant field (16 T) + margin… i.e 1500 A/mm²

Design a 16 T accelerator-quality model dipole magnet by 2018

Courtesy of M. Benedikt, FCC

Nb_3Sn: the workhorse of the “near Future”

Solid objectives for the FCC conductor R&D



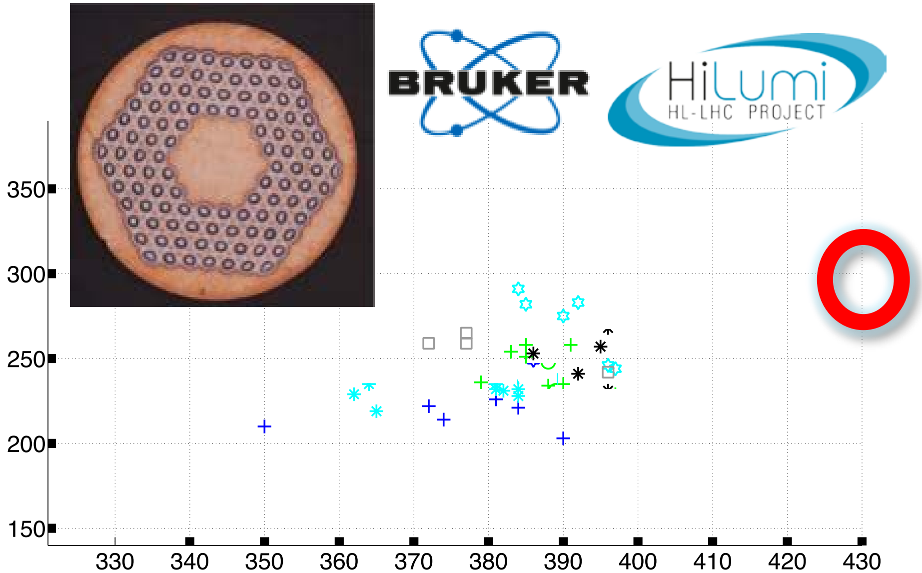
D_{strand}: 0.7…1 mm
J_C (16 T, 4.2 K) > 1500 A/mm^2
M (1 T,4.2 K) <150 mT (D_{fil} < 20 μm)
RRR > 150
UL > 5 km
Cost(16 T, 4.2 K) < 5 USD/kA m

Presentation given at “50+10 years”
Panel Session at the ASC,
Charlotte (US), August 10th-15th, 2014

The goal is ambitious but not impossible.
Cost wil be probably the most challenging

Conductor R&D

Specification: 1500 A/mm^2 @ 16T, 4.2K

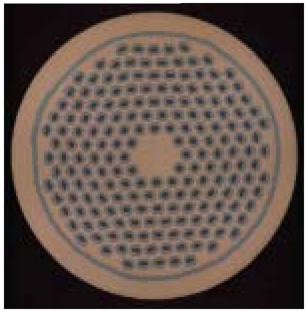


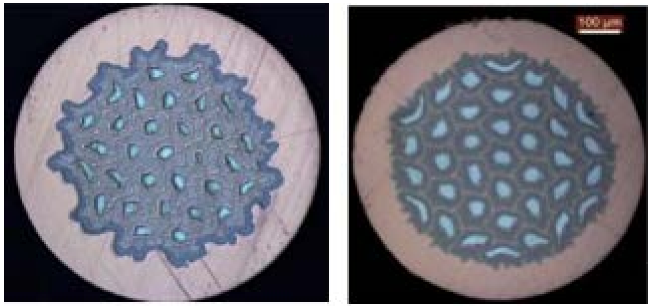
1750 A/mm^2 @ 15T, 4.2K

≈ 1400 A/mm^2 @ 16T, 4.2K

1274 A/mm^2 @ 15T, 4.2K

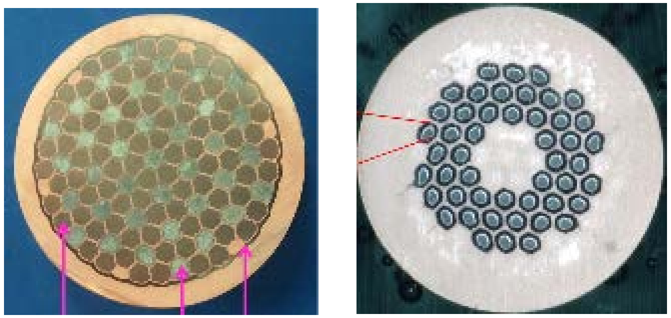
≈ 1000 A/mm^2 @ 16T, 4.2K



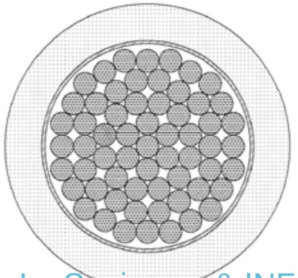


2850 A/mm^2 @ 12T, 4.2K

≈ 1250 A/mm^2 @ 16T, 4.2K



≈ 950 A/mm^2 @ 16T, 4.2K



FCC Magnet Designs

$T_{op} \approx 1.9$ K

I_{op}/I_C(loadline) ≈ 86 %

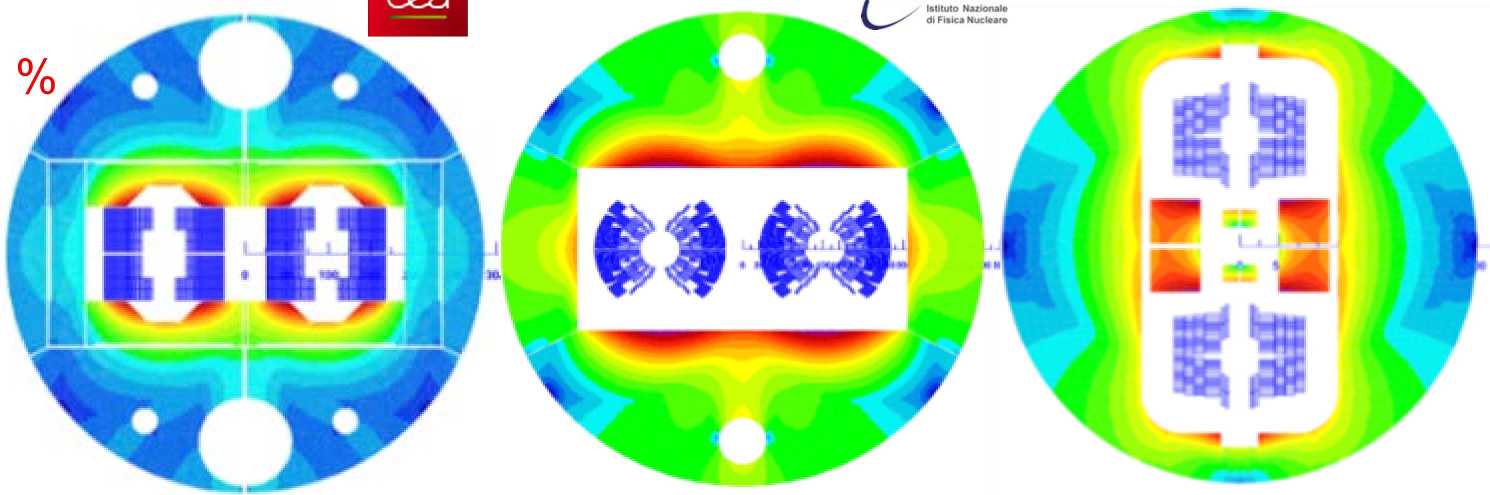
$V_{dump} < 2.5$ kV

$\sigma_{max} < 200$ MPa

$T_{hot} < 350$ K

$D_{out} \approx 600$ mm

HE-LHC !



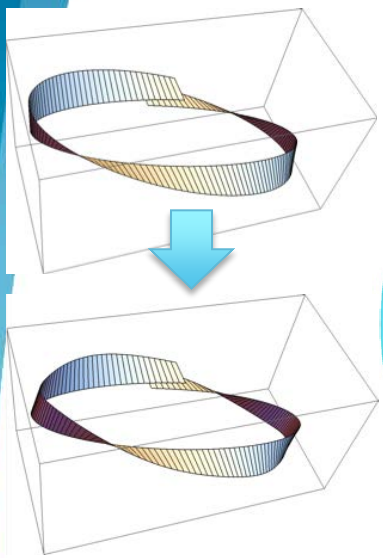
		blocks		cos(θ)		common coil
Current	(A)	11230		10000		16100
Inductance	(mH/m)	40		50		19.2
Stored energy	(kJ/m)	2520		2500		2490
Coil mass	(tons)	7400		7400		9200

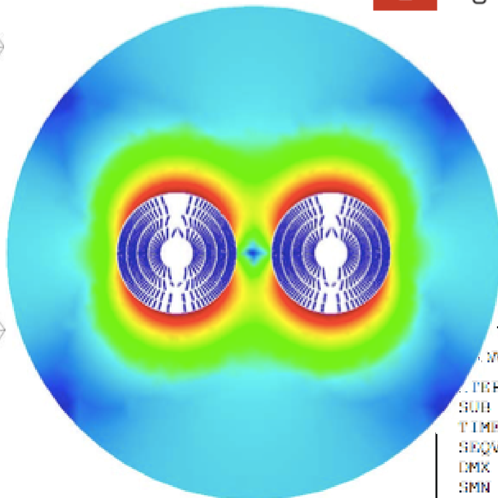
Very efficient use of superconductor (blocks, cos(θ))

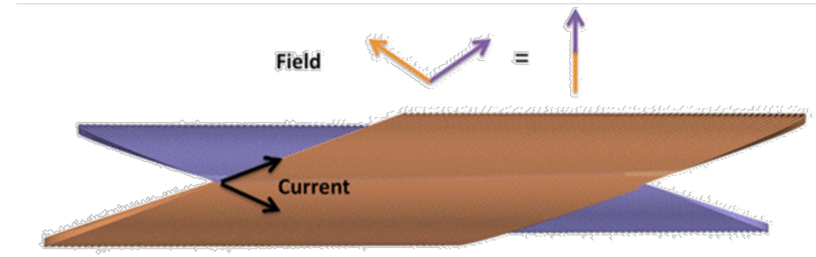
Simplified mechanics and manufacturing ? (common coil)

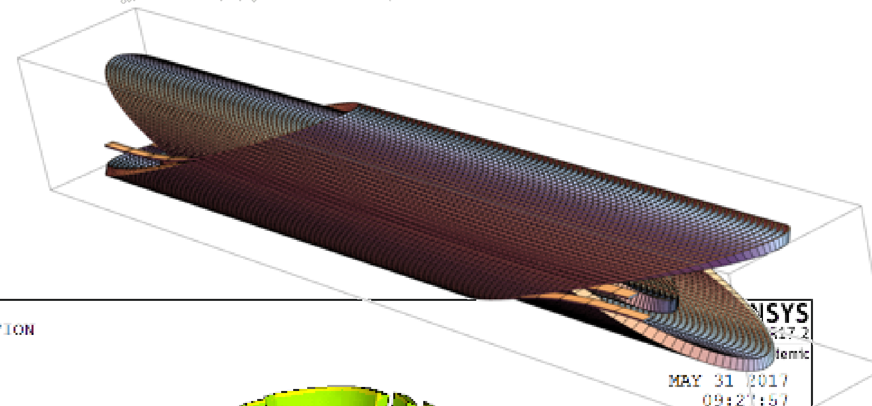
Courtesy of D. Tommasini, CERN

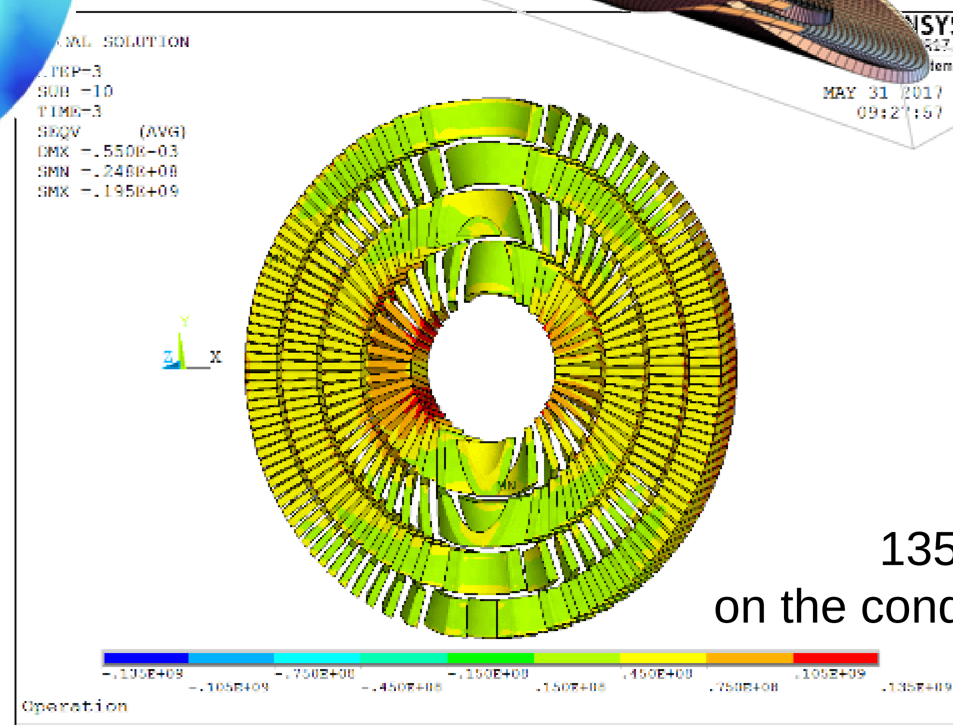
CCT option
Canted CosTheta









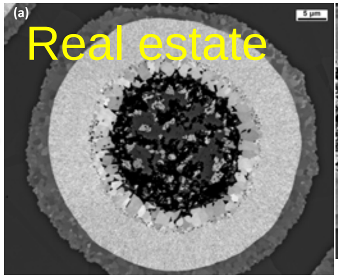


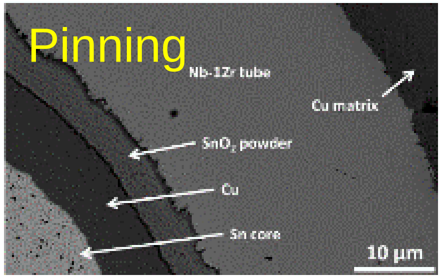
		CCT
Current	(A)	18055
Inductance	(mH/m)	19.2
Stored energy	(kJ/m)	3200
Coil mass	(tons)	9770

135 MPa
on the conductor

Courtesy of B. Auchmann, PSI and CERN

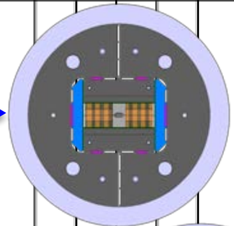
FCC 16T plan



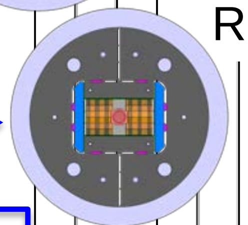


Conductor R&D

Activity	Begin	End	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
FCC Conductor Program	01.05.2015	31.12.2024																
Superconductor R&D program - phase I	01.01.2016	30.06.2020																
Superconductor R&D program - phase II	30.06.2019	31.12.2023																
State-of-the-art wire for demonstrators (150 km)	30.06.2016	31.12.2017																
Wire procurement for models and prototypes	30.06.2017	31.12.2024																
Core magnet technology R&D	01.01.2015	30.06.2021																
Design, manufacture and test of ERMC	01.01.2016	30.06.2018																
Design, manufacture and test of RMM	30.06.2016	30.06.2019																
FCC 16 T Models	30.06.2018	31.12.2022																
FCC 16 T Prototypes	01.01.2023	31.12.2025																
FCC Production	01.01.2026	31.12.2033																

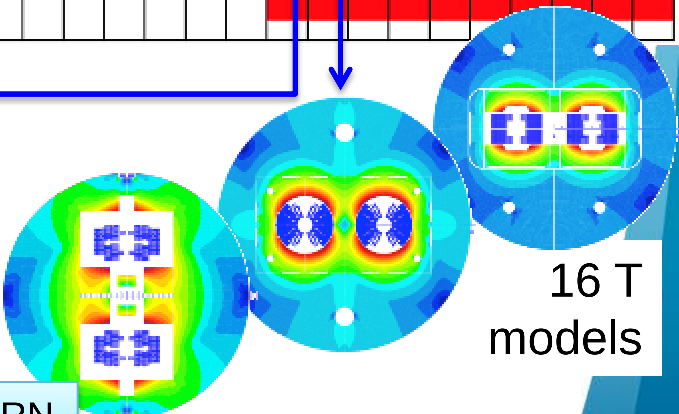


ERMC



RMM

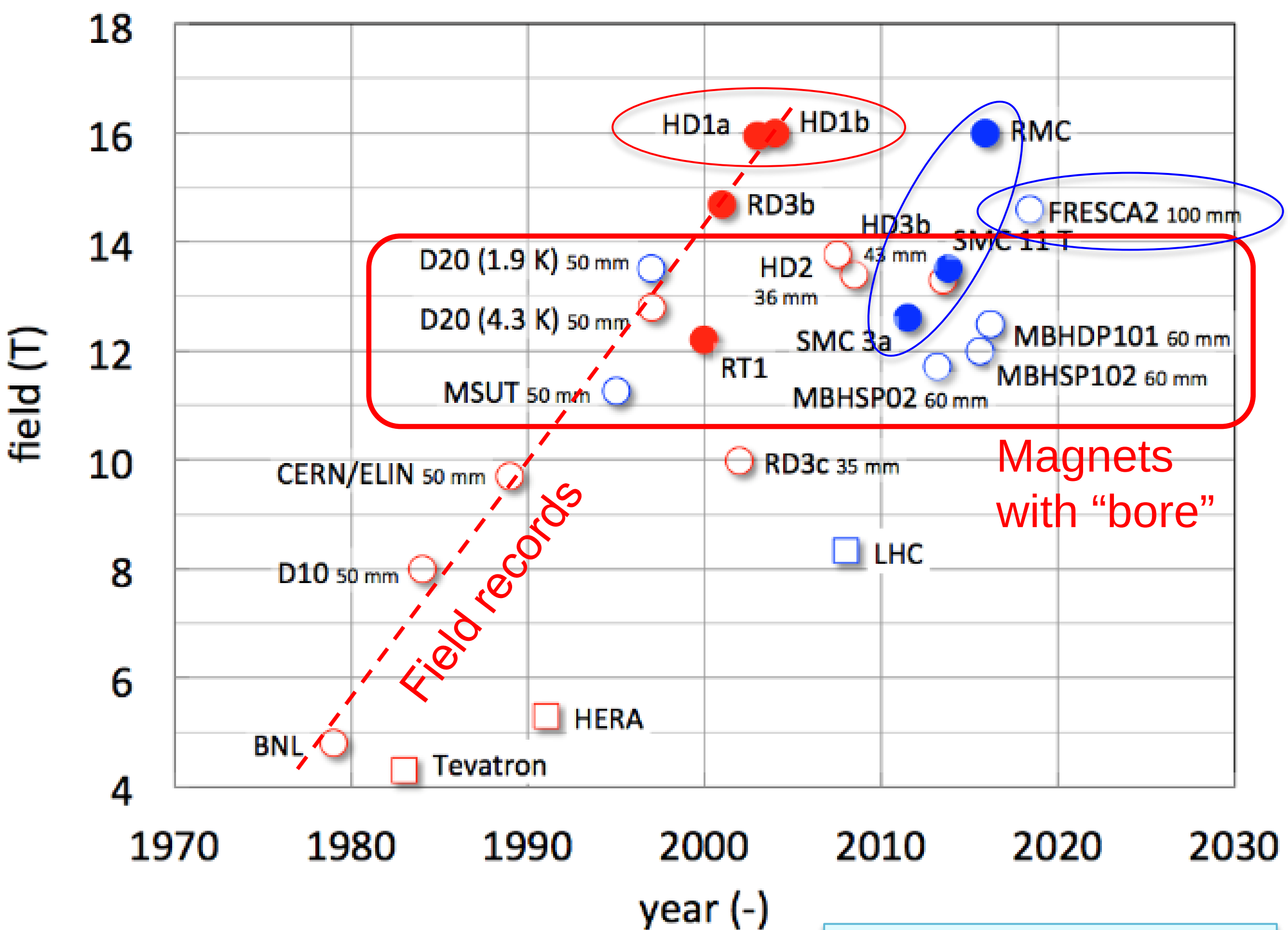
Opportunity for full length prototypes built in industry



16 T models

From Luca.Bottura-CERN

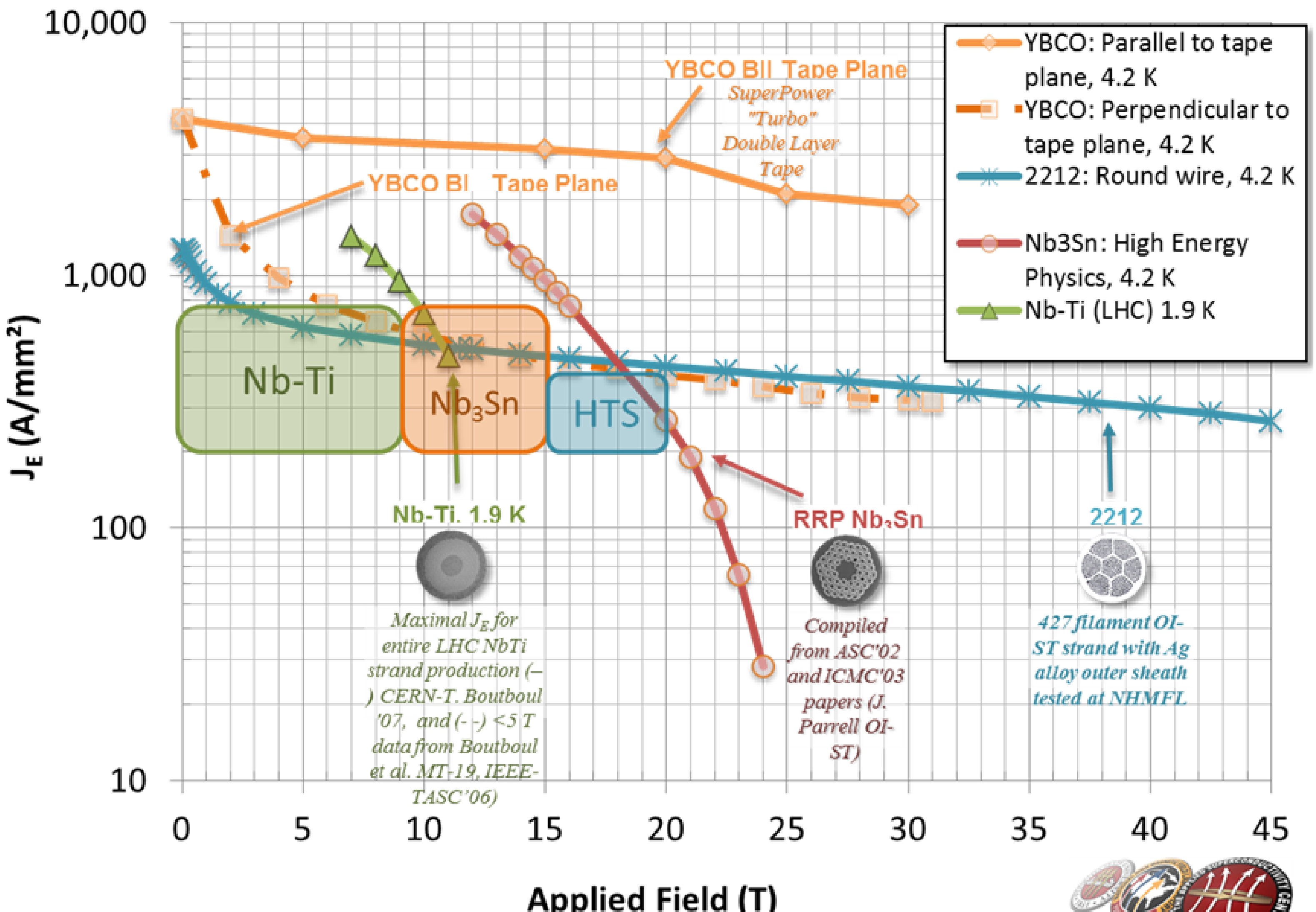
Highest “dipole” fields



From Luca.Bottura-CERN

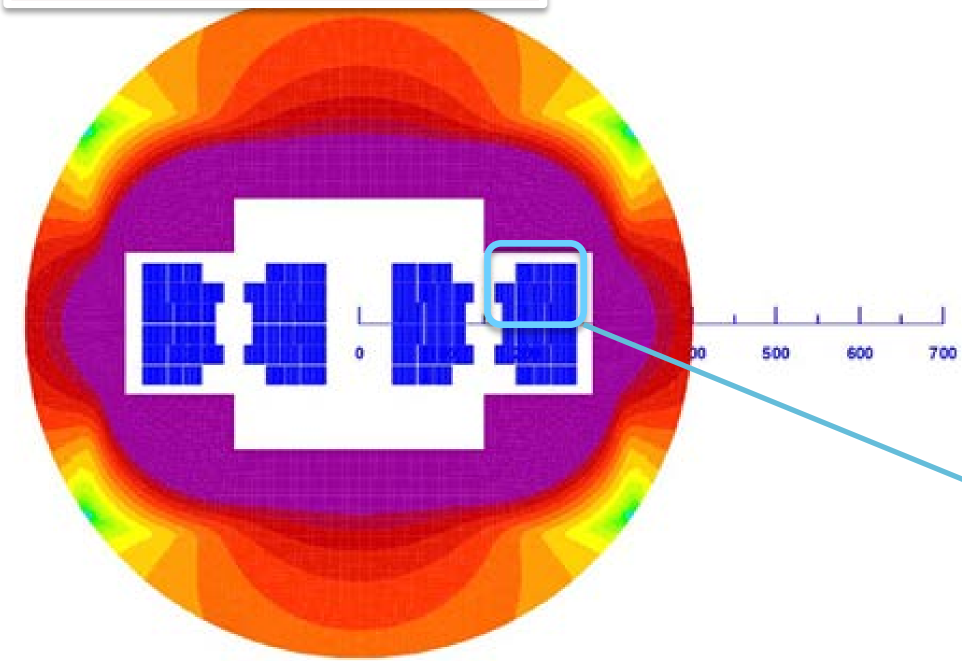
Record fields for SC magnets in “dipole” configuration

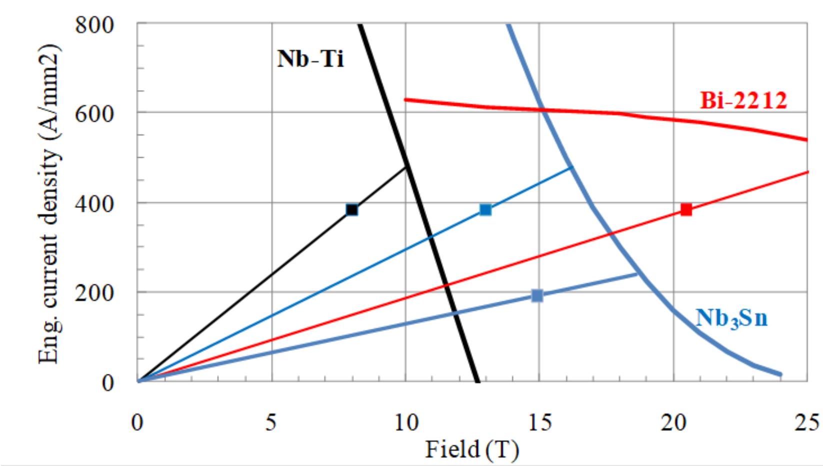
Are we stuck with 15-16 T of FCC? NO!

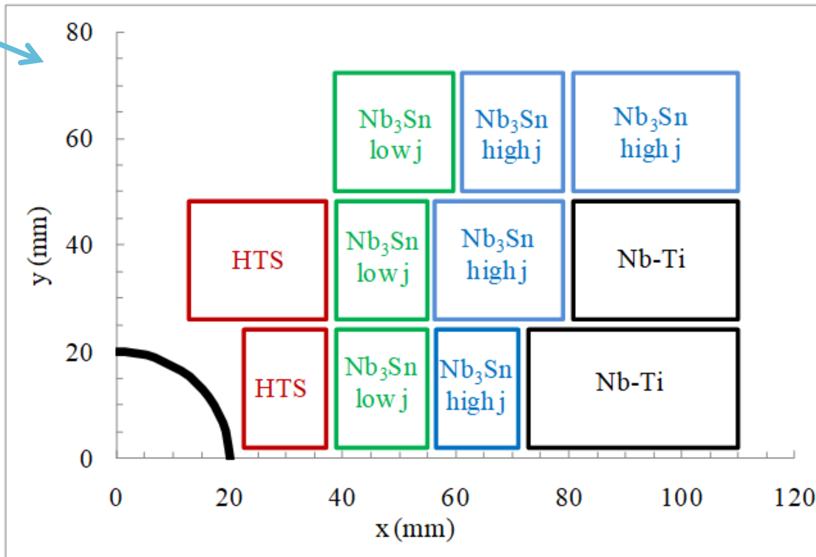


20 T dipole hybrid proposed in 2010 for HE-LHC

L. Rossi – E. Todesco

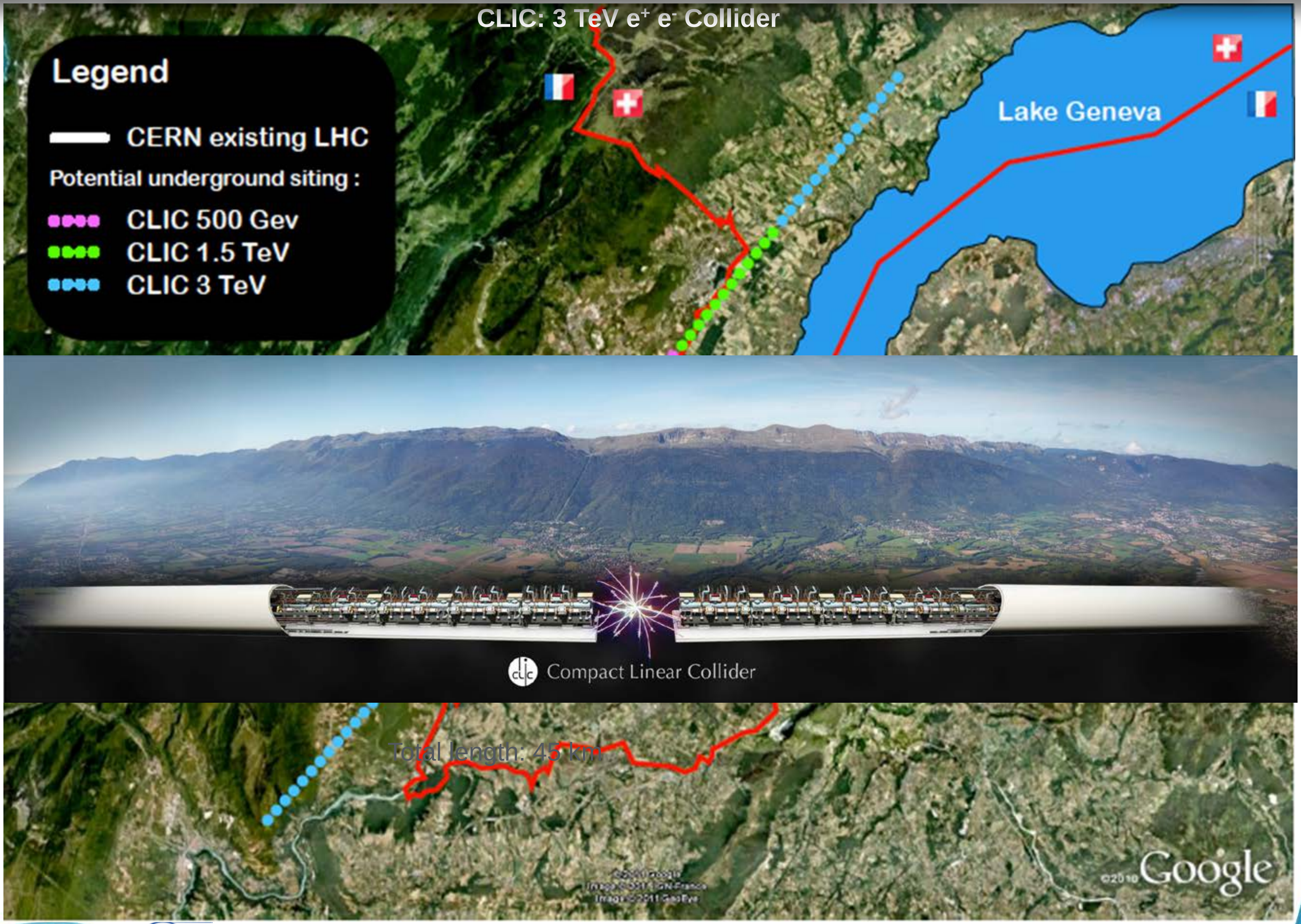




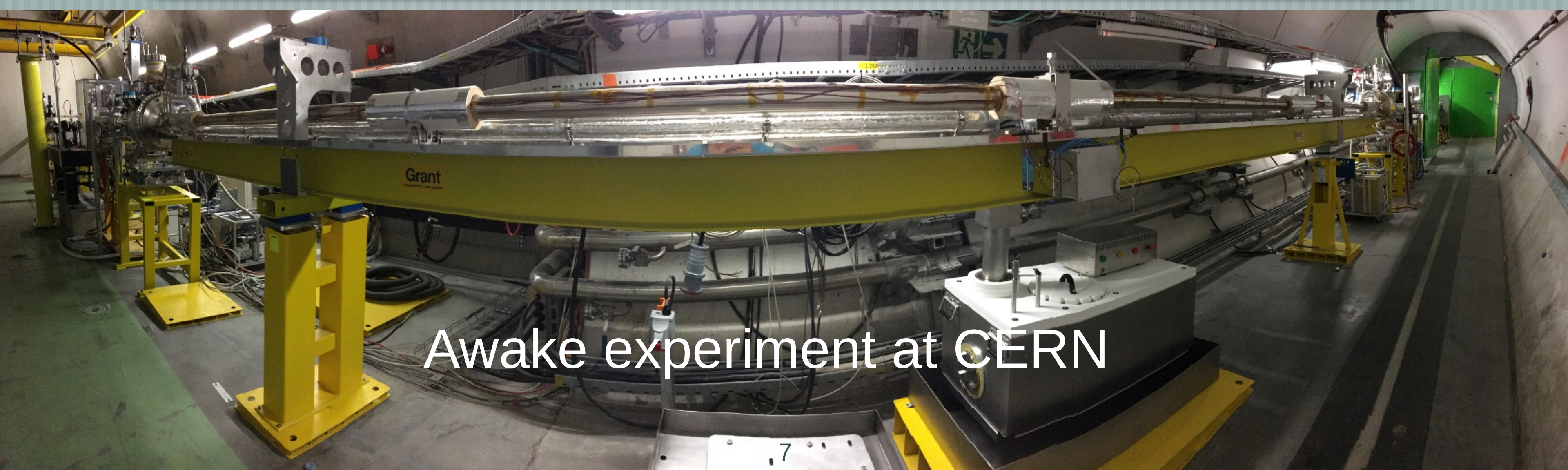


40 mm aperture
Now the standard is more 50 mm

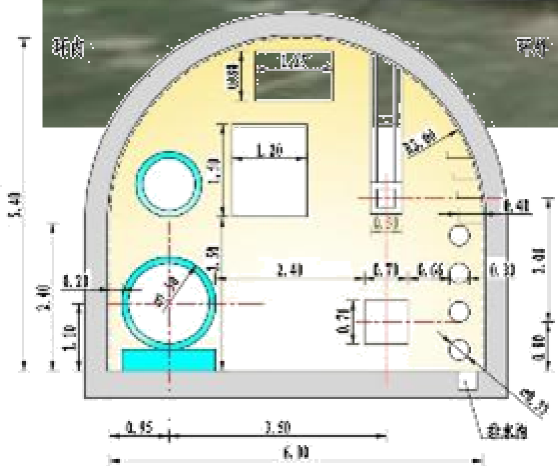
How to go to increase collision energy of constituents



Plasma acceleration: 1000 times smaller…
Or 1000 times more powerful?



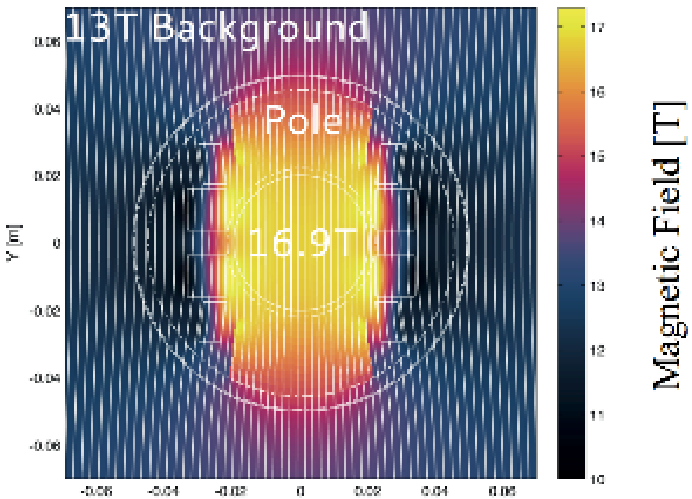
Super proton-proton Collider in China – Based on HTS

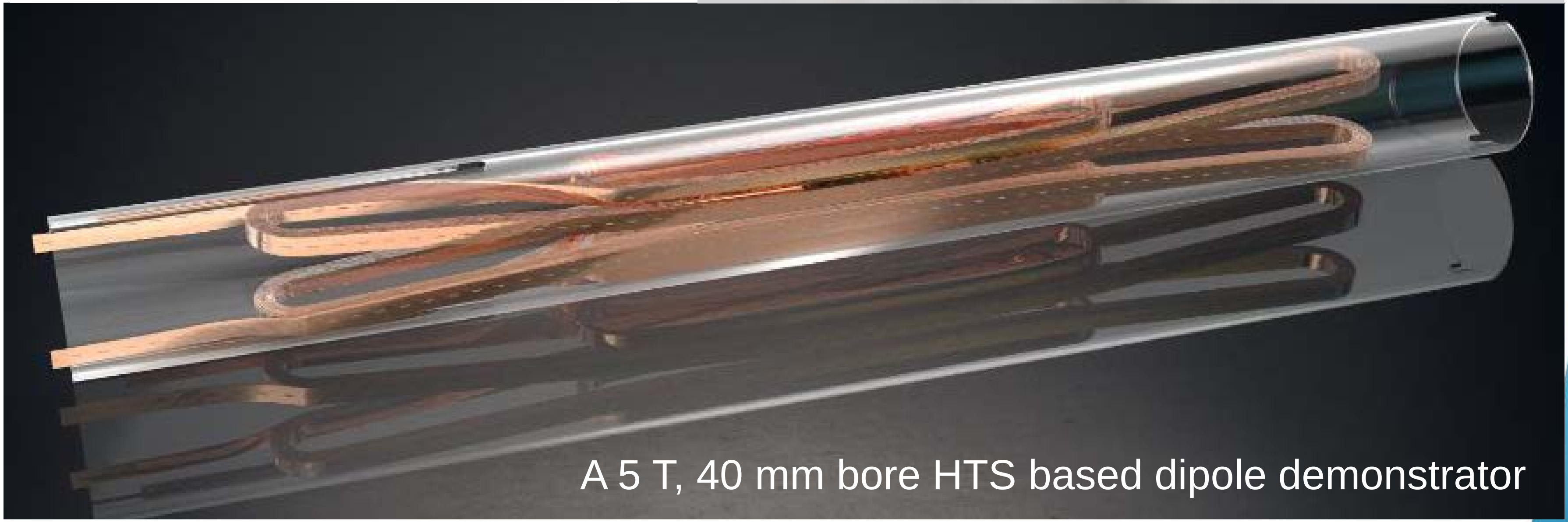


	LHC	FCC	SppC
Circumference (km)	26.7	97.5	100
Dipole field (T)	8.33	16	12…24
C.o.M. energy (TeV)	14	100	70…125

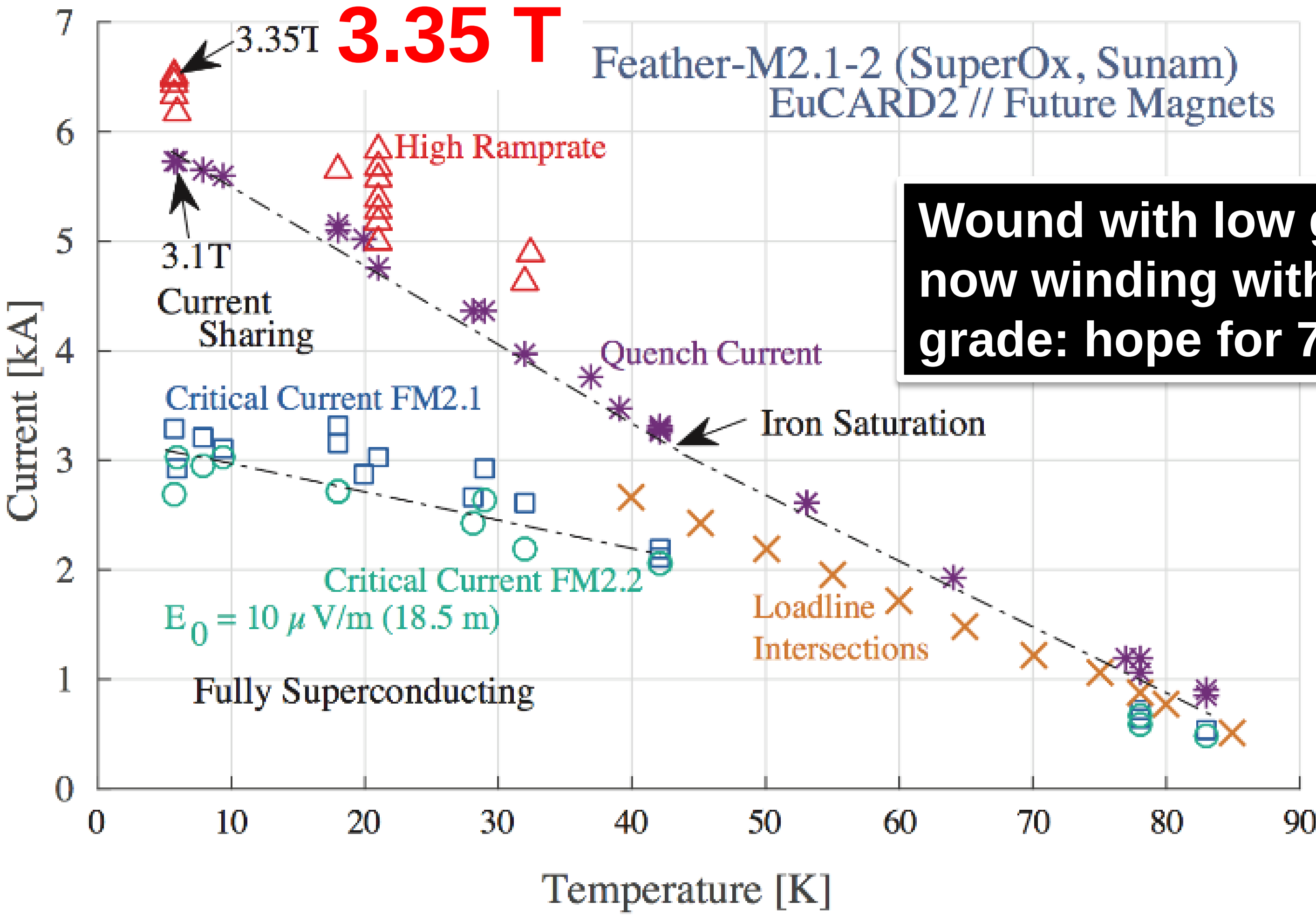
Courtesy of Q. Xu, IHEP, CN

Short accelerator dipole demonstrator
40 mm aperture, cable (not single element)



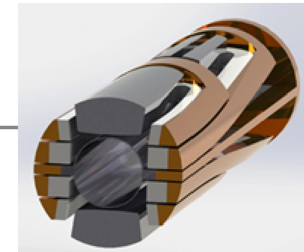


Dipole demonstrator results



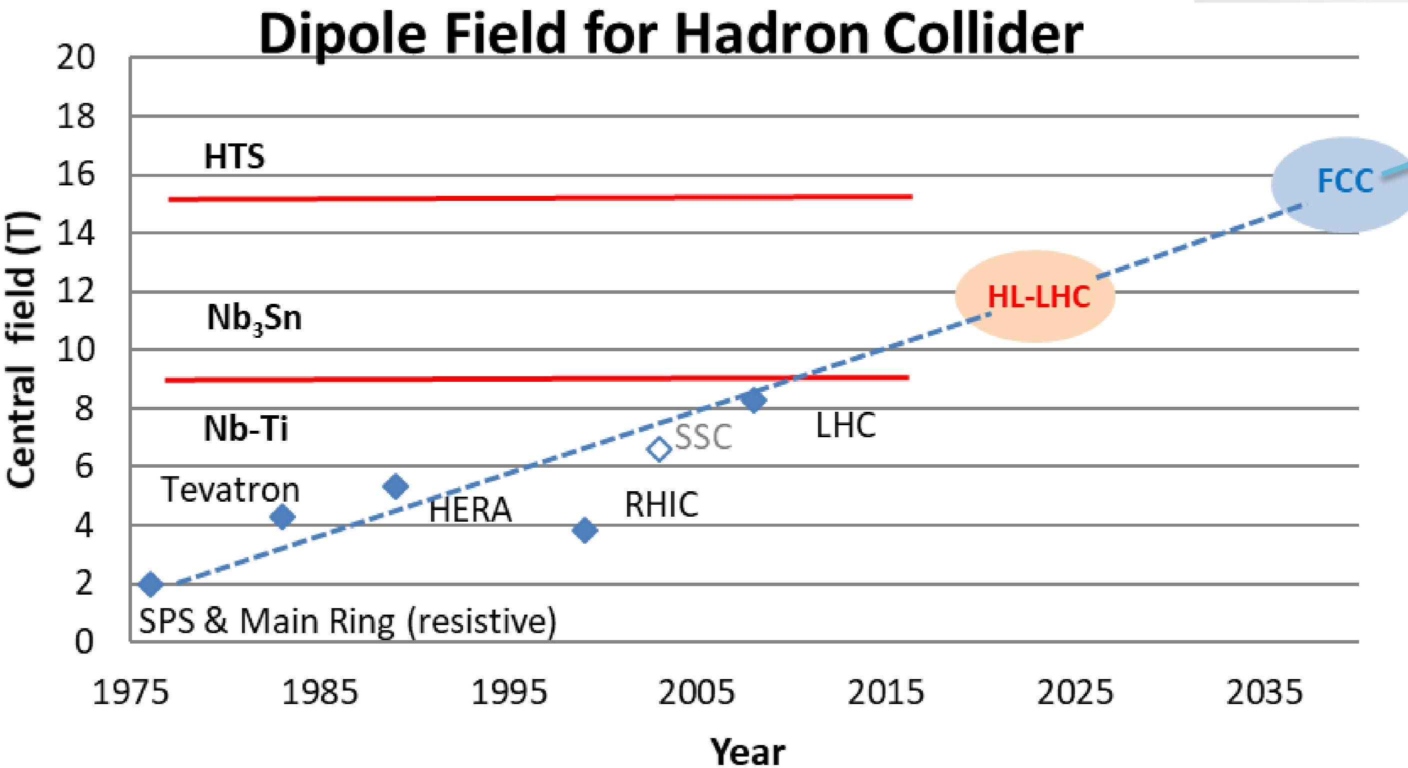
Wound with low grade SC, now winding with high grade: hope for 7+ tesla!

Can we extrapolate linearly from the past To go BEYOND FCC? ⇒ ELN?



EuCARD²

5T HTS demos

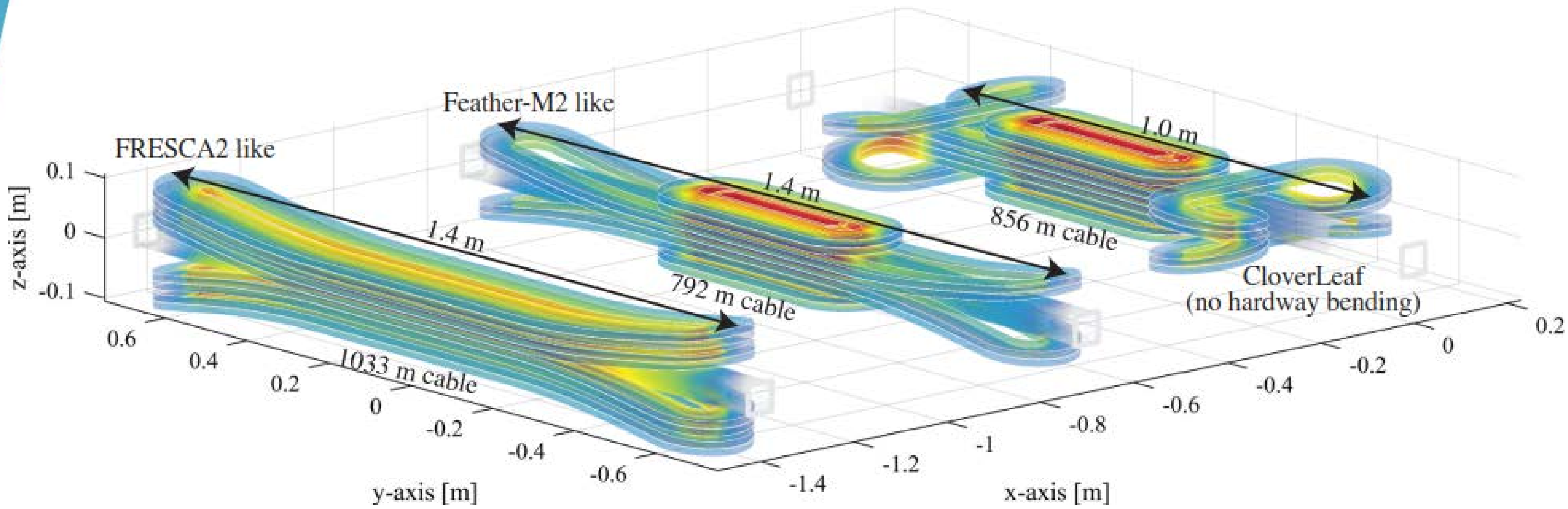


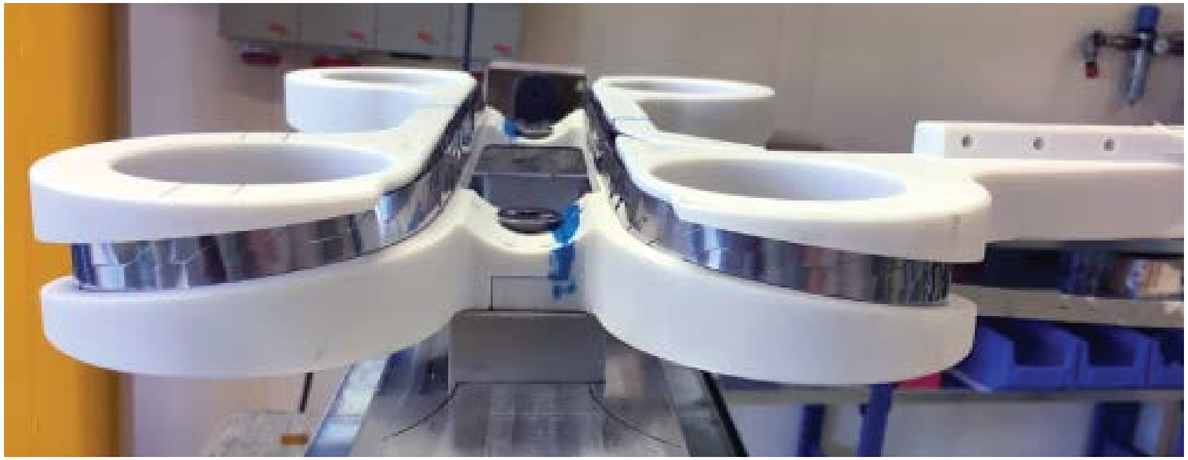
FCC (ELN)

20 T is not out of reach

2050

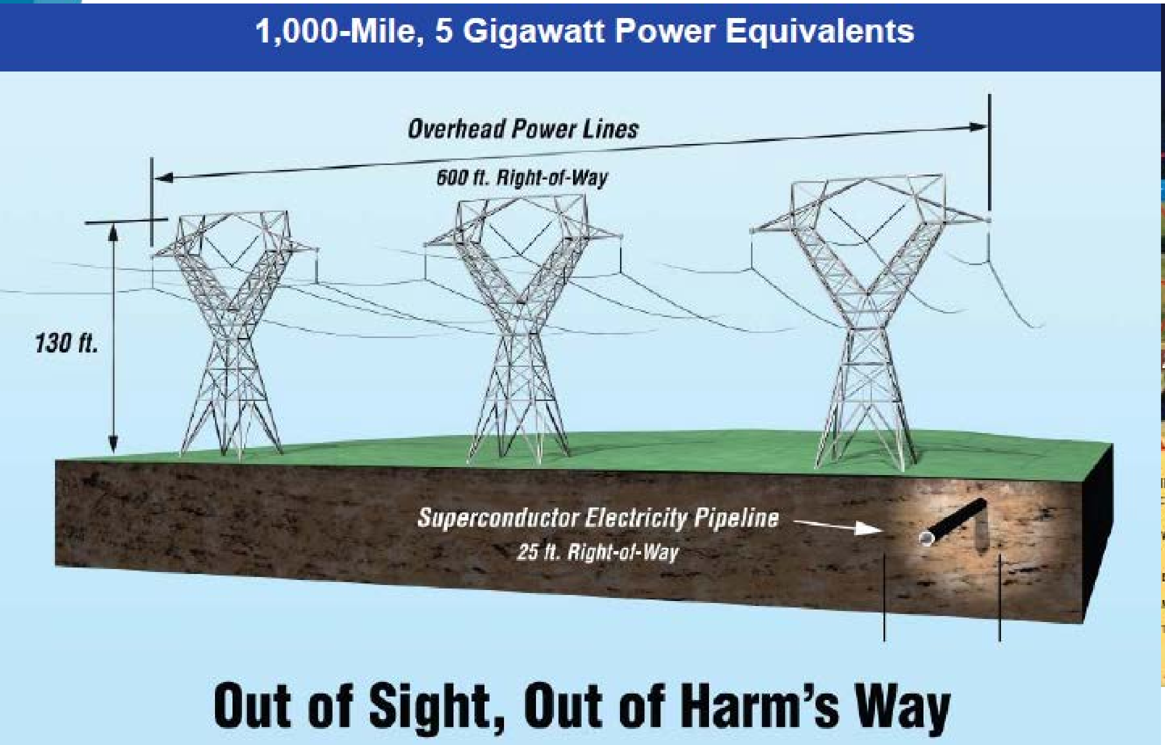
Working on unconventional desing of the end magnet shape





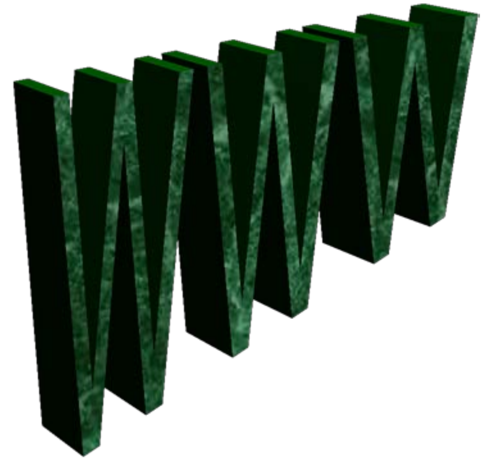
From Jeroen van Nugteren and Glyn Kirby -CERN

Superconductivity and Renewable Energy Technology



Courtesy Southwire Company

The legacy of HEP (CERN) : 30 years of WWW!!!



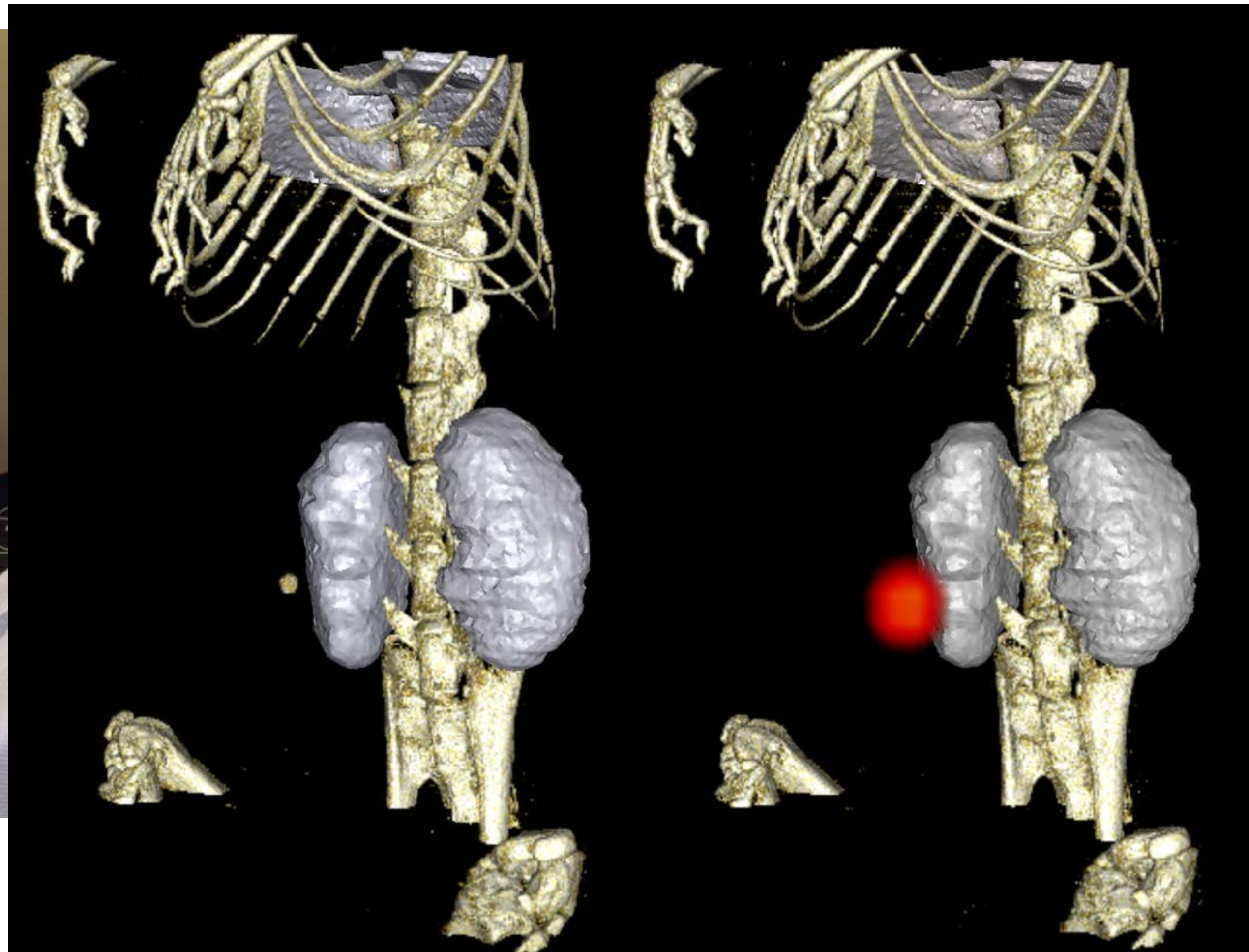
Tim Berners-Lee

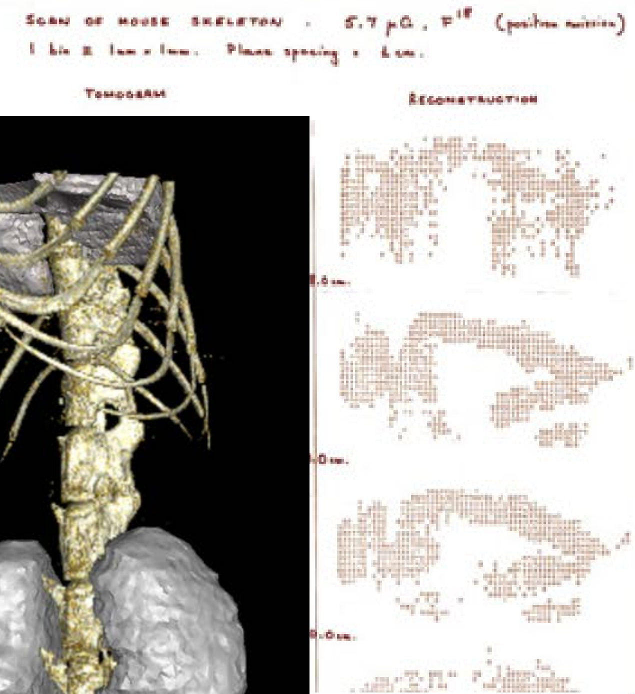
Robert Cailliau

1989 il WEB
2009 la celebrazione

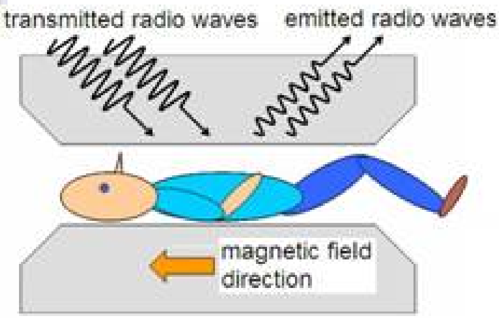
New medical «eyes»: PET

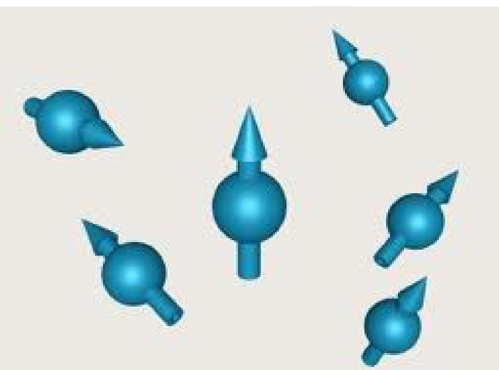
Prima immagine PET CERN, circa 1975

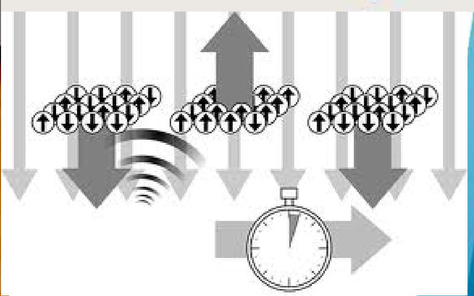




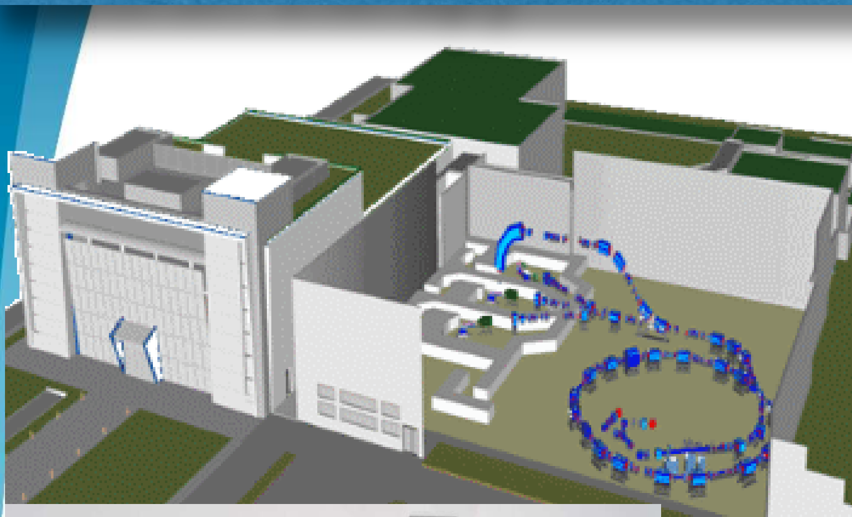
New medical «eyes»: MRI

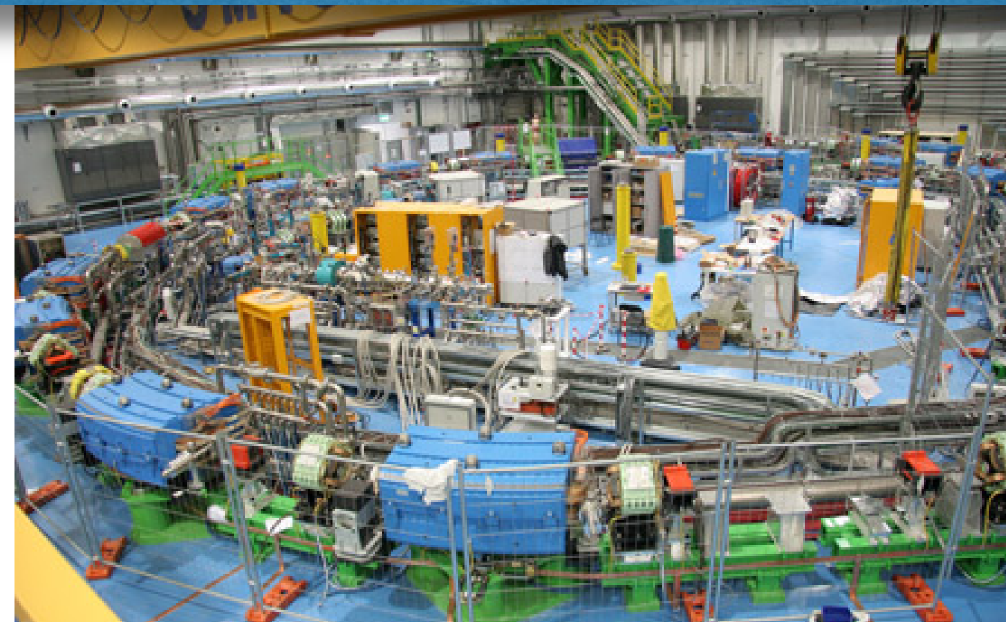




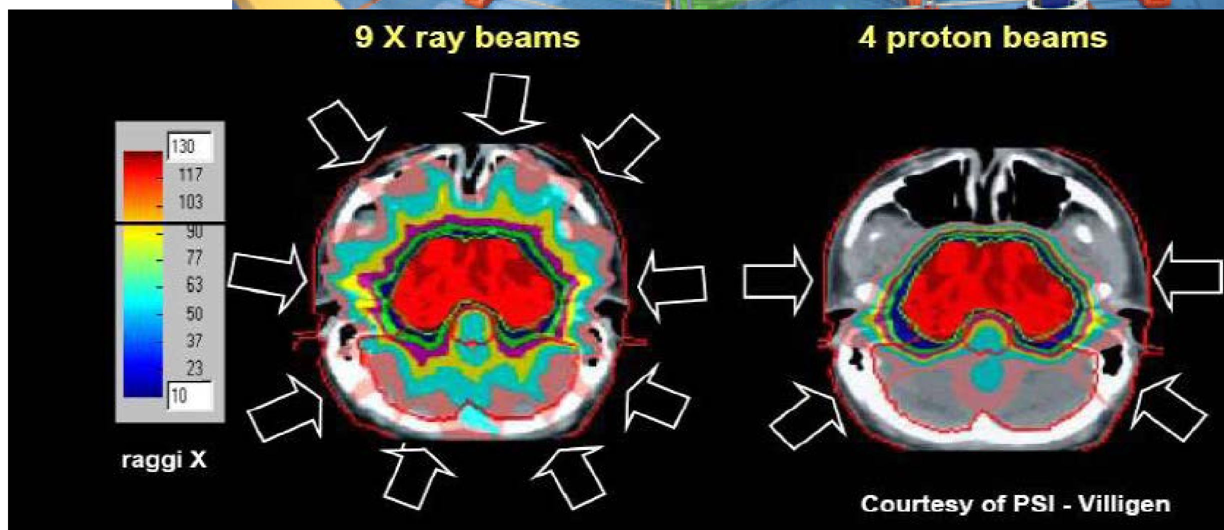


Hadron therapy

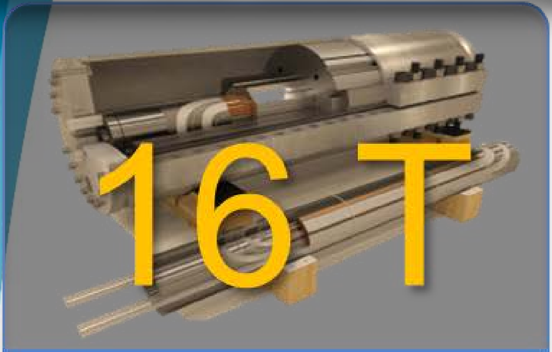




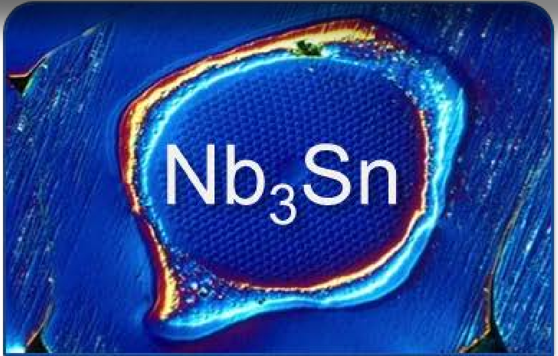
Ciclotrone SC



FCC is the natural evolution of HL-LHC but need further pushed technology advancement

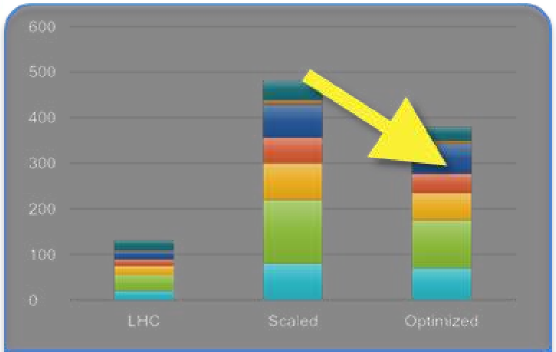


High-field Magnets



Novel Materials and Processes

Large-scale Cryogenics



Power Efficiency

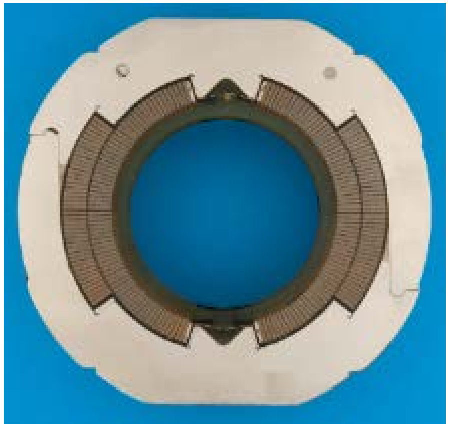
Reliability & Availability

Global Scale Computing

Stimulating innovation…

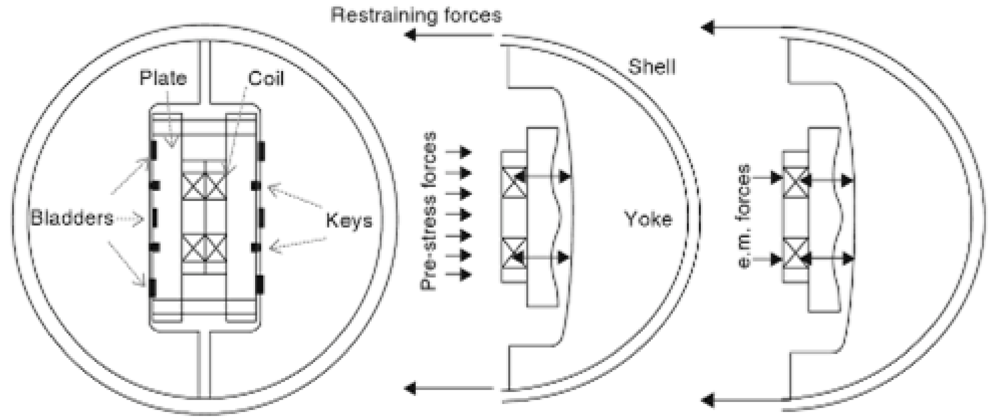

High
Luminosity
LHC
Thank you!

Old structures, new structures



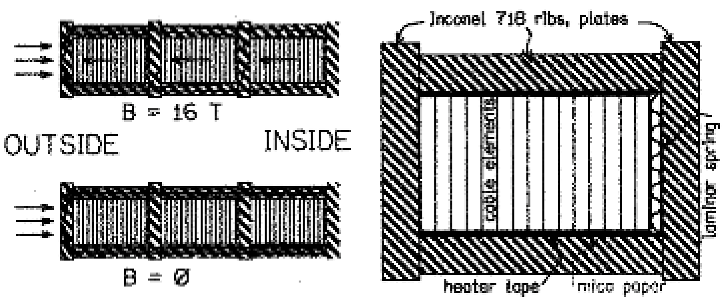
mid 1970's, FNAL: Collared coils

A. Tollestrup, Proc. Int Conf. on the History of Original Ideas and Basic Discoveries in Particle Physics, Erice (1994).



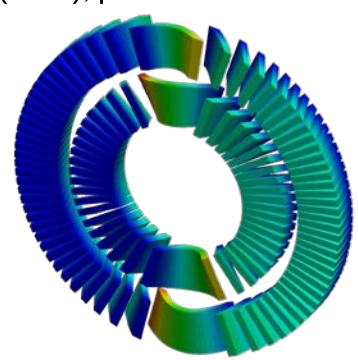
2002, LBNL: Bladder and keys

R.R. Hafalia, et al., IEEE TAS, 12(1) (2002), pp. 47-50.



1998, TAMU: Stress management

N. Diaczenko, et al., Proc. PAC, Vancouver (1997), pp.3443-3345.

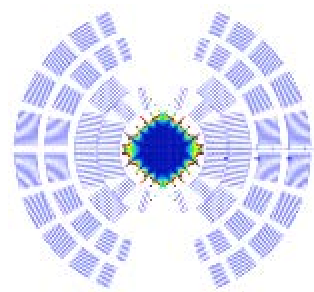


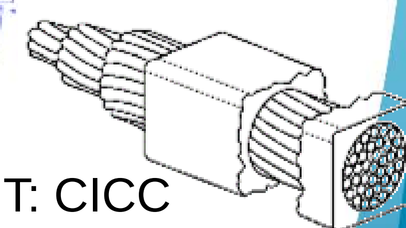
2014, LBNL: CCT

S. Caspi, et al., IEEE TAS (2014), p. 4001804.

2017, FNAL: SM cos(θ)

V. Kashikin, et al., Proc. IPAC, Copenhagen (2017), pp. 3597-3599.





1975, MIT: CICC

M.O. Hoenig, et al., Proc. 5th Magn. Tech. Conf., Frascati(1975), p. 519.